MECHANICAL PROPERTIES

OF

MATTER

BY

S. G. STARLING, B.Sc., A.R.C.Sc., F.Inst.P.

MACMILLAN AND CO., LIMITED
ST. MARTIN'S STREET, LONDON
1946

First Edition 1935.
Reprinted, with additions, 1937.
Reprinted 1940, 1944, 1946.

PRINTED IN GREAT BRITAIN

PREFACE

UNDER the title of General Physics, or Properties of Matter, it is usual to include the fundamental laws and principles of matter and motion, or what are known as Mechanics and Hydrostatics. Though these mechanical properties of solids, liquids and gases form a necessary part of the instruction in the most elementary course of physics, their full significance cannot be understood without a fair equipment of the mathematical principles involved. In this book, which is chiefly intended for students preparing for Higher School Certificate, or Intermediate Examinations in Physics, it is assumed, therefore, that they are acquainted with the operations of the differential and integral calculus.

It was formerly customary for work in these subjects to be deferred to a later stage. This, however, is no longer the case, for nearly all candidates for the Higher School Certificate receive instruction in the calculus as part of their mathematics course for this examination. But though the needs of these students have been borne particularly in mind, the book is not written for the syllabus of any one university, and subjects are included for the sake of continuity which may not appear in any syllabus.

Both classes and individuals vary much in their attainment, so that the choice of reading for the student must be left to the teacher. It should be remembered that the same examination serves not only to discriminate between passing and failing candidates, but also for the awarding of scholarships. It is, therefore, usual to set some questions of a more advanced character than the others, and it is hoped that this book will help the candidate in the more advanced as well as in the elementary parts.

Many points have been elaborated by means of examples, most of which are taken from examination papers.

Acknowledgments are due to those examining bodies which have kindly allowed questions to be taken from their Higher School Certificate examination papers, namely, the University of London

(L.H.S.C., Int. and B.Sc.); Oxford and Cambridge (O. and C.H.S.C.); Cambridge (C.H.S.C.); Oxford (O.H.S.C.); Joint Matriculation Board (J.M.B.H.S.C.); and Central Welsh Board (C.W.B.H.S.C.).

I must express my very great indebtedness to Sir Richard Gregory for help in all stages of the work, and to Mr. A. J. V. Gale for a number of suggestions made upon the proofs; also to Mr. H. J. Gray, B.Sc., for reading the manuscript and working out the examples.

1935. S. G. STARLING.

CONTENTS

CHAPTER I

VELOCITY AND ACCELERATION

General considerations.—The study of Nature begins with an examination of those phenomena that appeal directly to the senses. From sight and touch we obtain the idea of distance or length. From the muscular exertion required to set a body in motion we realise the quantity which we call "force," and the sequence of events gives us an instinctive feeling which we call "time." Hearing, colour sensation and taste are other primary sensations but with these we are not concerned here.

In choosing units for the measurement of physical quantities it is necessary to bear in mind that each unit must be constant and convenient. The unit of length chosen is the **metre**, the distance between two marks on a platinum-iridium bar preserved at the International Bureau of Metric Weights and Measures at Sèvres near Paris, when the temperature of the bar is 0° C. One hundredth of this, or one centimetre, is commonly used as the unit of length for scientific purposes. The unit of time is the mean solar second, or 1/86400 of the average time taken by the earth to make one complete rotation with respect to the sun.

One more unit must be defined before it is possible to measure the majority of physical quantities. There is a choice between force and mass. If either of these is given, the other can readily be defined, and the question will be discussed more fully when Newton's laws of motion are given (p. 25).

The quantity **mass** is chosen in preference to force, for its standard is easy to preserve and convenient to compare with other masses. Mass is a property of matter which is easy to realise, but difficult to define. Everyone knows that it is easier to set in motion a floating cork than a ship. This is chiefly because the ship has the greater mass. The standard of mass used in scientific work is a piece of platinum-iridium preserved at Sèvres and called the **kilogram**. One thousandth part of this is taken as unit and called the **gram**. Thus we measure our physical quantities in centimetres, grams and seconds; hence this is called the C.G.S. system.

On the British system the foot, pound and second are used, and

PLATES

CHAPTER I

Historical

FROM the very smallest of beginnings the science of electricity arose. The simple experiment of rubbing a piece of amber with wool and watching light bodies dance up to it had provided an amusement for centuries before its importance was suspected. The turning to the pole of a balanced piece of lodestone, though of more practical use than the experiment with the amber, was not considered of great importance. Yet unexplained and unimportant effects are sometimes the only outward expression of great and universal laws. The growth of the other branches of physical science causes no surprise. The possession of the sense of sight renders the development of the science of optics, or light, almost a necessity, for every inquiring mind must seek for explanation of the agency which produces vision, since the phenomena connected with it are of perpetual occurrence. Sound, or acoustics, naturally follows from our sense of hearing; and warmth, or heat, with the accompanying effects of combustion, expansion, and contraction, has given us a similar study. From the various forms in which matter can occur, chemistry has arisen.

But no one would connect the experiments of the amber and the lodestone with any particular organ of sensation; they remained mysteries until, early in the last century, newly discovered effects led to a connection between these and others, and from them an abstract idea was evolved which should unify them all. Such is the normal development of science: from single and apparently unconnected

effects, hypotheses are laid down, which, on being put to the test of further experiment, are verified or, as frequently happens, are modified, until with fuller understanding it is seen that some underlying principle connects them all. But electricity laboured under the great disadvantage with respect to the other sciences that the human frame does not possess any sense organs which detect the presence of electrification or magnetisation.

No one could have thought a century or so ago that the two simple effects with the amber and the lodestone would eventually lead to the vast organisation of industry and research which goes under the name of electrical engineering, or to the explanation of such varied phenomena as light and chemical affinity; or lead to the discoveries of radioactivity, in which new elements are seen in the act of being evolved from others; or the world atmosphere threaded with a maze of signals carrying messages, and even the human voice, from continent to continent. On looking back, the science which we call ELECTRICITY is seen to have grown in a manner more marvellous than any of the other branches of knowledge. The growth at first was slow, but by the patient work of the earlier experimenters, the foundations were laid which gave rise to the marvellous progress of this century. It is our object in this little book not to trace the history of electricity but to give some intelligent account of its present position. But it follows that simple ideas must be studied before those which are more complex can be grasped, and since the science itself must be developed from the elementary to the abstruse, it follows that every intelligible treatment must be historical to some extent.

From the earliest times it has been known that amber (ἤλεκτρον) when rubbed with dry cloth or fur exhibits the property of attracting light bodies. Later it was found that other substances, such as sealing-wax and glass, had the same property, but the actual origin of the discovery is lost in antiquity. William Gilbert, at the close of the sixteenth

century, attributed these effects to a force which he called ELECTRIC. Thus the word ELECTRICITY had its origin; but it is now known that the cause of these simple phenomena is also the cause of other and far more complicated effects.

The discovery that a certain mineral, oxide of iron, or lodestone, will, when freely suspended, set in one particular direction is of very early origin and was certainly known to the Chinese many centuries ago. The mineral was found at Magnesia in Asia Minor, from which is derived the modern term, MAGNET, that is applied to it when used as described. The mineral is likewise called magnetite. On suspending a piece of magnetite, either by hanging it up by a silk fibre or by floating it upon a piece of wood on water, the piece turns round until a certain part of it is directed towards the north, the opposite part towards the south. The usefulness of this phenomenon was known in the Middle Ages, when this device was used in the form of the magnetic compass or mariner's compass. Although the direction indicated by the compass is not everywhere true north and south, the constancy of the indication of the compass is sufficient for it to be of considerable assistance in navigation. In fact, it is still the chief guide in the steering of all ships, although it has been so modified that a modern ship's compass bears very little resemblance to the suspended lodestone of the ancients. The reason why the discovery of the magnet is included as one of the origins of *electrical* knowledge may not be clear to the reader. For years, even centuries, the phenomenon exhibited by amber and that exhibited by lodestone appeared to have no relation to each other. However, the whole tendency of modern work in this subject makes it more and more evident that magnetism and the electric current are inseparably connected and probably never occur apart. And, further, it will become evident as we proceed that the most useful and beneficial effects of the electric current are possessed on account of its magnetic properties. This is so true that it may even be doubted

whether the two subjects should be separated, as is customary, and whether the consideration of magnetic properties as apart from electricity is permissible.

A third origin of our knowledge of electricity can be more definitely stated than the two already mentioned. It is the accidental discovery by Luigi Galvani in 1780 that on touching one of the chief nerves of a freshly dissected frog with the point of a scalpel, at the time that the prime conductor of an electrical machine in the neighbourhood was discharged, the limbs of the frog were violently convulsed. In order to investigate the effect of atmospheric electricity upon the nerves of the frog, specimens were hung up out of doors on an *iron* lattice by means of *brass* hooks passing through the spine. Galvani found that on pressing the *brass* hooks into an *iron* lattice, convulsion of the limbs of the frog took place. It was eventually found that when the muscles and nerves were connected by any external metallic circuit, part of the circuit consisting of one metal and the other part of a second metal, convulsions always occurred. Whenever the circuit consisted partly of a non-conductor of electricity, such as wood, wax, etc., there were no convulsions.

This is a prime discovery, because up to that time electricity had only been produced by friction. The effects produced by the contact of different metals or of metals and certain liquids was long known as GALVANISM, and the term still remains in the names GALVANIC BATTERY and GALVANOMETER and the verb TO GALVANISE, both in the sense of exciting to activity and in the sense of GALVANISING sheet iron.

Galvani failed in his attempts to intensify the effect by increasing the size of the pieces of metal he used in the circuit, although some pairs of metals were found to be more efficacious than others. It remained to Alessandro Volta in 1800 to find a means of intensifying the Galvani effect. By taking a number of discs of copper, zinc, and moistened pasteboard and building them up into a *pile* in

the order copper-pasteboard-zinc-copper-pasteboard-zinc, etc., a very much magnified galvanic effect could be obtained, and by touching with one hand the lowest copper disc and at the same time touching the uppermost zinc disc with the other hand, a distinct shock could be felt, similar in character to that caused by an accumulated electric charge produced by frictional means.

Our knowledge of electricity may be traced from these three humble origins. As in all other branches of knowledge, progress has been made by patient and industrious workers who pursued their labours with no thought to the possibility of their commercial application. It is true that the technical application of scientific principles has led to an enormous development of their everyday usefulness, but the fact cannot be too frequently emphasised that such application has not given rise to any new principle. The discoveries that have revolutionised modern thought and life might all have been called useless and worthless by the people who consider nothing of value that does not lend itself at once to commercial use.

As an intellectual study, electricity presents a field for the highest and most complex types of mathematics, as well as for the reasoning powers of the more direct and realistic type. As an interesting study to those who, without special mathematical training, wish to follow its more practical aspects, none presents so rich a field. The experimenter may find useful material everywhere. A few dry cells and some insulated wire afford more variety for interesting experiment than anything else obtained with as little trouble, while, on the other hand, the following of complex apparatus used in the more abstruse branches of the subject afford difficulties sufficient to satisfy the most intellectual.

Electricity, then, belonged to one of those apparently useless and inexplicable though interesting phenomena down to the time of Michael Faraday, who in 1831, after long seeking, found the most important link between

electric and magnetic phenomena, to which the possibility of producing electric power by mechanical means is due. In order to put the reader in possession of the knowledge necessary to understand this effect, a brief review of the chief electrical and magnetic phenomena will now be given. But in order to present this in the clearest manner, the historical order of the discovery of these phenomena will not be followed.

Starting with the simplest phenomenon in magnetism—the setting of the lodestone or natural magnet in one direction and its picking up of iron filings—it may next be observed that the filings cling more particularly at two places on the body. These are also the places which point north and south when the specimen is suspended, and were discovered by Petrus Perigrinus (1269), who called them POLES. The pole which points to the north when the specimen is suspended is called the north-seeking or N. pole, and the other the south-seeking or S. pole. The production of artificial magnets led to the discovery of the force between magnetic poles by John Mitchell (1750). If a rod of hard steel be rubbed from one end to the other with the pole of a piece of lodestone, the rod itself becomes a magnet and exhibits all the magnetic properties of the lodestone. There are now other much more powerful means of magnetising steel, which we shall see later, but the strong magnets so produced are identical in properties with the early forms, the only difference being that of strength.

On obtaining two magnets and suspending one of them by a fine thread or floating it on wood upon water, and approaching the other magnet to it, using each pole in turn, it will be seen that two N. poles repel each other, that is, there is some force pushing them apart. In the same manner two S. poles repel each other, but a N. pole and a S. pole attract each other. Thus the fundamental law upon which the study of magnetism rests is that MAGNETIC POLES OF LIKE KINDS REPEL EACH OTHER, AND POLES OF UNLIKE KINDS ATTRACT EACH OTHER.

On placing a compass needle near a magnetised bar of steel, the N. pole of the compass is attracted by the S. pole of the bar magnet and repelled by its N. pole. Likewise, forces in the reverse directions act upon the S. pole of the compass. Under these forces the compass will come to rest in some particular direction, and by testing at various positions near the magnet, it soon becomes obvious that the directions are related to each other in a very beautiful manner. The bar magnet being represented by NS in Fig. 1, the direction in which the small compass will set is shown at *ns*. By moving the compass about, lines round the bar magnet may be found such that wherever the compass may be placed, its direction is always that of the line on which it happens to be situated. The lines must, from the nature of the forces between magnetic poles, arise on the N. poles, spread out, and eventually converge on the S. pole. These lines may be exhibited in a very elegant manner by placing a piece of paper or a sheet of glass on the magnet, and sprinkling iron filings on the sheet. On gently tapping the sheet, the filings will arrange themselves along lines similar to those of Fig. 2. In this way Fig. 2 has been obtained for a pair of bar magnets situated so that the N. pole of one is near the S. pole of the other. Faraday was particularly struck by the fact that magnetic fields may always be mapped out by means of such lines, and called them MAGNETIC LINES OF FORCE. It is therefore clear that a freely suspended small magnet will always set itself along a magnetic line of force, its N. pole being urged in one direction along the line and its S. pole in the opposite direction. Hence Faraday insisted upon the peculiar

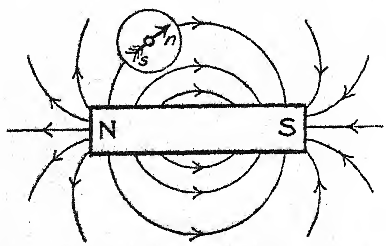


FIG. 1. Determination of the magnetic lines of force due to a bar magnet by means of a compass.

condition of the space around a magnet, and gave to these lines of force a reality which has proved of first-rate importance in studying magnetic effects. Indeed, it is impossible to overestimate the importance of the effect

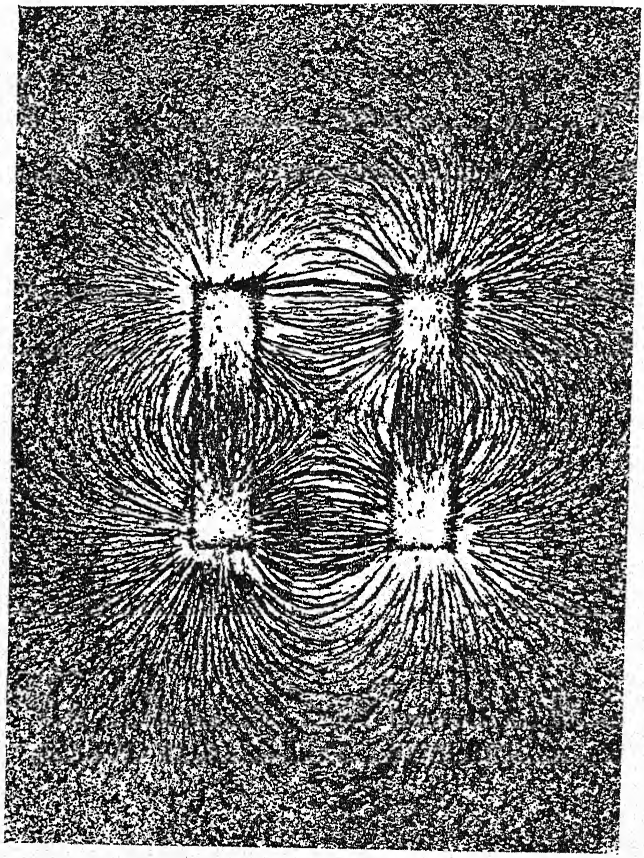


FIG. 2. Magnetic lines of force of a pair of bar magnets, exhibited by means of iron filings.

which the conception of lines of force has had in the study of electricity.

An interesting and simple experiment may be carried out by taking an ordinary sewing needle, which is made of

fairly hard steel, and stroking it from the point to the eye with the N. pole of a bar magnet several times. This suffices to magnetise the needle. It may now be pushed halfway through a small piece of cork, so that it will float horizontally on the surface of water placed in a cup or saucer. On removing the bar magnet and all other magnetic materials from the neighbourhood of the floating needle, it will be found that it will soon settle down to one particular direction, the point being directed towards the north; the floating needle constitutes a simple form of magnetic compass. By bringing another needle, similarly magnetised, near to the floating needle the rule for the force between magnetic poles may be established. It will be found that two poles of the same kind repel each other and poles of opposite kind attract each other. For use as an instrument of precision, the needle takes the form of a little bar of steel, usually tungsten steel, carefully hardened by heating to red heat and plunging in water, before being magnetised. The needle is supported on a steel point or pivot which fits into an agate cup on the needle. In the best patterns the pivot and the cup are of sapphire, the hardness of which causes the retention of a fairly sharp point and minimises the friction at the point of support.

From very early times there has been much speculation as to why the suspended magnetic needle should point north and south. William Gilbert, in 1600, published a work in which he gave an explanation of the behaviour of the compass, which was near the truth. He explained its action by saying that the earth itself is a large magnet, and he constructed a model of the earth in the form of a sphere or terrella of magnetite which behaved towards a little magnet placed near it very much as the earth behaves towards the magnetic compass. Such a model of the earth must have the kind of magnetisation in its northern half that is possessed by the S. pole of the compass needle, because opposite kinds of pole attract each other. Also the magnetic lines of force would run from one pole to the

other, following the course of geographical lines of longitude.

While producing a very fair rough model of the earth's magnetic condition, Gilbert made one mistake of importance; that is, he considered the magnetic poles of the earth to be at the same places as the geographical poles. Now a careful observation of the position in which a compass needle sets shows that the needle does not point true north, and that the deviation from the true north varies from place to place on the earth's surface. In England, at the present time, the compass points about 10° west of true north. This amount, called the MAGNETIC DECLINATION, or by mariners, the VARIATION OF THE COMPASS, is different at different places. Along a line passing through North America, the Gulf of Mexico and the southern Atlantic, the declination is zero, the compass pointing due north. Similarly on the other side of the world is another line of zero declination, although this is more irregular than the American line. Between these two the declination varies, getting greater up to about 20° W. in mid-Atlantic, and 10° E. in mid-Pacific. The lines of equal declination are not regular, like the lines of longitude, but their general course is north and south. The magnetic pole was found by Sir James Ross in 1831 to be situated in Labrador, at a point whose longitude is 96° 43′ W., and latitude 73° 31′ N.; while the magnetic south pole was found by Shackleton's south polar expedition in 1909 to be situated longitude 155° 16′ E., latitude 72° 25′ S. Charts are prepared and issued by the Admiralty giving the declination at all points on the earth's surface, and the rates at which it is changing, so that in navigating by the compass, the correction required to reduce a compass bearing to a true bearing may be found.

The mariners' compass in use up to the middle of the last century was very imperfect. It consisted of a card attached to which were the magnets, the card having the points of the compass marked upon it, and a line showing

the central line of the ship, or "lubber line," marked upon the case. The old compass cards were both large and heavy and consequently sluggish in movement, and the pivots were so imperfect that sticking of the card was of frequent occurrence. Further, the use of iron in the building of ships introduced new errors, which rendered the compass of very little value, until after the mathematical investigation of the magnetic field on iron ships was made by Poisson and Airy in 1838. After this, the field due to permanent magnetisation of the ship was corrected by small permanent magnets placed in the binnacle, and the effect of temporary magnetisation of the soft iron in the ship was corrected by means of two soft iron spheres, one on either side of the compass.

The imperfections in the compass itself were not removed until Lord Kelvin, then Sir William Thomson, took up the question, and removed the marked imperfections of the older forms. Lord Kelvin made improvements in two particular directions. First, the card was made very light, being a thin wire ring with a paper disc, cut out in the centre, the points of the compass being marked on the paper. This may be seen in Fig. 3, which is a drawing of a 10-inch Kelvin compass card. The lightness of the card, together with improvements in the pivots, reduced friction to a minimum. Secondly, the magnets were short steel needles, four, six, or eight in number, slung by threads in the central space cut from the card disc. As Kelvin showed, it would require enormous iron spheres to correct for the soft iron magnetisation of the ship with the long magnets of the older type; but with short magnets the spheres are reduced to a manageable size, and the correction is good. Spheres of 12 ins. diameter are generally employed. The compass is so designed that the period of oscillation of the card is about 30 secs., and is longer than the period of rolling of the ship. In this way the excessive disturbance set up by the rolling of the ship is avoided. Lord Kelvin produced his type of compass in 1873, and

since that time it has been adopted universally for marine service. The only improvement since that time has been the filling of the compass bowl with liquid, which reduces still further the effective weight on the pivot, and also serves to damp out any disturbing oscillation of the card.

With the growth of aeronautics new types of compass have been devised. For the difficulties at sea are as nothing compared with those in the air. When an aeroplane takes a proper turn, the compass does not remain

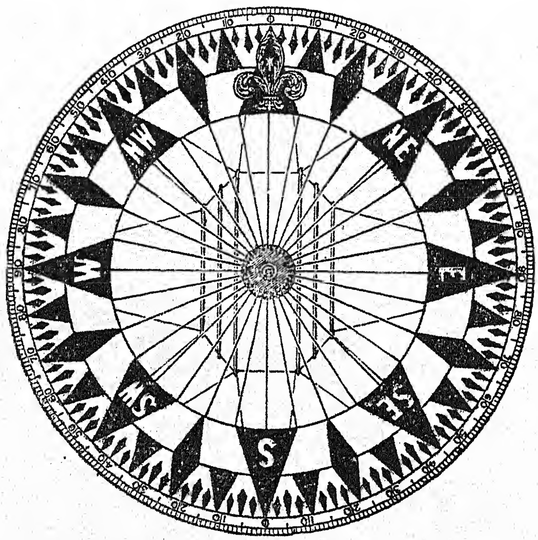


FIG. 3. Kelvin compass card.

horizontal, but takes the same tilt as the machine. One of the latest types of aeroplane compass is seen in Fig. 4. The light card, with strong magnets, is seen in the centre of a bowl which is nearly spherical, and filled with methylated spirit. The anti-vibration supports are seen, and a small incandescent lamp is placed for use at night, although many of the compasses are provided with points marked in radium paint so that they are self-luminous.

We must now take up the thread of our account of the

discovery of the electric current itself. If the metallic discs at the end of the voltaic pile (p. 4) are connected together by means of a fine copper wire, it will be noticed that the wire becomes warmed, and if a modern battery be employed instead of the voltaic pile, the wire may be heated to such an extent that it is fused. It was also found that the wire at the same time is capable of producing an effect upon a magnet. This was discovered by Hans Christian Oersted in 1820, who observed that a

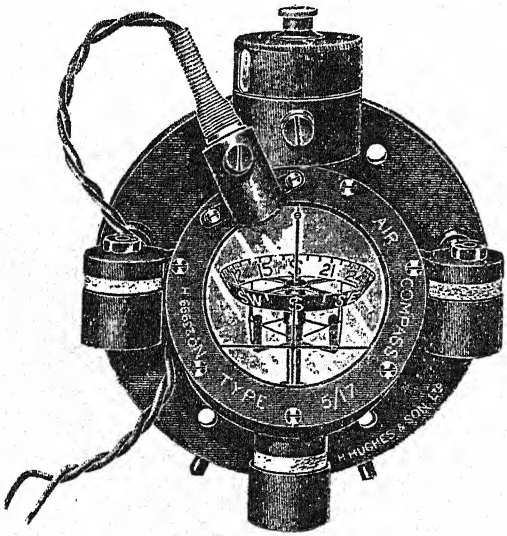


FIG. 4. Aeroplane compass.

suspended magnet tended to set in such a position that it is at right angles to the wire. By these two effects an electric current is recognised. There are other effects due to a current, but the influence upon a magnet and the heating of the wire are the two most important, because these two are employed in nearly all the applications of electricity.

The discovery of Oersted is worthy of particular notice. Owing to its peculiarity it was sought for some time in

vain. In all the examples of force between bodies known up to the time of Oersted's discovery, the force is exerted in the line joining the bodies concerned. Thus, in the case of gravitation, two bodies attract each other, and if free to move, will approach each other. Two magnetic poles either attract or repel each other, but the force acting on either is in the line joining the two. A magnetic pole, however, is not attacted towards, or repelled from, a wire conveying an electric current, but experiences a force in a direction at right angles to the current and also at right angles to the line joining the pole to the current. In Fig. 5, if AB is a wire carrying the electric current, a magnetic N. pole situated at C experiences a force urging it in the direction CD, at right angles to both AB and to CE, the perpendicular from C to the wire. If the magnetic pole at C were a S. pole the force would be in the direction opposite to CD, but would still fulfil the stated conditions. It follows, therefore, that a magnet, which of course has a N. pole at one end and a S. pole at the other, would, if suspended, set as shown at *ns* in the diagram; in fact, a straight wire carrying an electric current is surrounded by magnetic lines of force which are circles having their centres upon the wire.

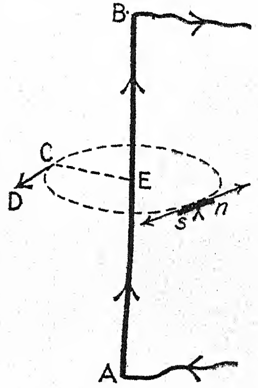


FIG. 5. Magnetic field due to a straight wire in which an electric current is flowing.

One other effect of an electric current, which was discovered by William Nicholson and Anthony Carlisle in 1800, must be mentioned. On setting up the first voltaic pile made in this country (in order to repeat Volta's experiments) and completing the circuit by a drop of water, gas was evolved where one of the wires entered the water, the other wire becoming oxidised. On using platinum wires to dip into the water, gas was evolved at both wires; the

gas collecting on one being hydrogen, and that on the other oxygen. This process was afterwards called ELECTROLYSIS by Faraday, and the liquid through which the current passes an ELECTROLYTE, and the conductors by which the current enters and leaves the liquid, ELECTRODES. With the exception of liquid metals, such as mercury, the only liquids which are capable of conducting an electric current are solutions of certain salts and acids, and the salt or acid is decomposed as the current passes. The hydrogen on the metal is always liberated at the electrode by which the current leaves, which is called the CATHODE, and the acid radicle is liberated at the electrode by which the current enters, which is called the ANODE. In Fig. 6 the anode and cathode are shown. If we consider a typical electrolyte, such as a solution of sulphuric acid (H_2SO_4) in water, the hydrogen (H_2) of the sulphuric acid is liberated at the cathode, and being a gas it bubbles away. The $[SO_4]$ being the acid radicle is liberated at the anode. But this is a substance which cannot exist alone, and with the water it forms again sulphuric acid. The water, being a compound of hydrogen and oxygen (H_2O), gives up its hydrogen to the sulphuric acid, thus—

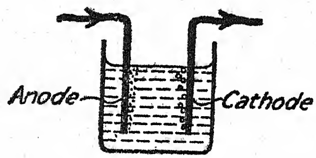


FIG. 6. Electrolytic cell.

$$[SO_4]+H_2O=H_2SO_4+O$$

The oxygen being a gas forms bubbles which escape through the liquid, but it should be noticed that the oxygen is not produced by electrolysis, as was originally thought, it is the result of the reaction of the $[SO_4]$ liberated by electrolysis with the water of the electrolyte.

In many cases of electrolysis the substance deposited is in the metallic form. Thus, if the electrolyte consists of a salt of copper, silver, or gold, the metal liberated at the cathode is in the pure metallic form. On choosing a suitable

body on which to deposit the metal, this body becomes coated with the metal, and is said to be ELECTROPLATED. The industrial process of electroplating and electrotyping need only be mentioned here in order to indicate the important uses to which the knowledge has been put. It will be described more fully in a later chapter.

It may, however, be noted that one of the earliest discoveries made by means of electrolysis is due to Sir Humphry Davy, who passed the current through fused soda. A metallic bead was formed at the cathode, which was thus the newly discovered metal sodium. Potassium was in the same way liberated from fused potash.

One of the most important investigations of Faraday was undertaken to find out whether the two electricities, that produced by friction and that produced by a battery, were one and the same. He succeeded in establishing the fact that the two were identical, and that every effect produced by one could, under suitable conditions, be produced by the other. The electricity produced by friction is at rest upon the body on which it makes its appearance. But whereas some bodies are incapable of allowing the electricity to move upon it, others allow it to pass easily from one place to another. The former are called INSULATORS or DIELECTRICS, and amongst the most important of them we may note: dry air, amber, paraffin wax, mica, gutta-percha, silk, and shellac. Those substances which will allow electricity to pass freely along them are called ELECTRICAL CONDUCTORS, and, generally speaking, include the metals and certain solutions, which we have seen are called electrolytes. The best conductor of electricity is silver, but pure copper runs it very close. Arranged in order of conductivity, they are: silver, copper, gold, aluminium, zinc, iron, platinum, tin, nickel, and mercury.

Between the good insulators and the good conductors, the great majority of substances would lie, and these are never used for electrical purposes.

Faraday, then, showed that if the electricity produced

by friction were placed upon a conductor it could move along it, and in so doing it was capable of producing all the effects due to the electric current derived from a cell or battery, that is, it can produce magnetic and electrolytic effects. But it must not be supposed that the two sources are equally suitable for the production of an electric current. For the current derived from frictional sources is extremely feeble in comparison with that from a battery, although the electricity produced by friction can form a spark by jumping across air spaces of considerable amount. It would require a battery of many thousands of electric cells to cause a spark to jump across an air space a quarter of an inch in length, if the wires had not previously touched, although such a spark can be produced quite easily on rubbing an ebonite rod with a piece of fur and approaching the hand to the ebonite. As an analogy we may liken the current produced by a cell or battery to a river, in which a great quantity of water passes, although the difference of level between neighbouring parts is small. The spark produced from the ebonite must then be considered to be similar to a raindrop which falls from a great height but contains a very small quantity of water.

Electricity at rest exhibits very different properties from electricity in motion. There is no magnetic effect due to electricity at rest, the study of which is called ELECTROSTATICS. Electricity in motion is called ELECTRIC CURRENT, and its most important distinction from electricity at rest is that it is always associated with a magnetic field. A study of the electric current leads to the treatment of all the useful applications of electricity, and it will be our object to trace these from their origin in the laboratory and to see how they are employed for scientific and industrial purposes. In the great majority of these applications of the current, it is the magnetic effect which is of greatest importance.

We have seen that an electric current flowing in a wire produces a magnetic field, and that a piece of iron or steel in this field becomes a magnet and attracts other pieces of

iron or steel. Hence the current brings into play forces which may be utilised in various ways. This is, in brief, the principle of the electric telegraph, in which a piece of iron is magnetised by the current and attracts a second piece of iron; in the telephone, in which the variation in a current causes a variation in magnetisation and of attraction between a piece of iron and a thin iron diaphragm; and it is also the basis of many other electrical appliances. Thus the electric motor, which supplies the motive power for electric trains, trams, and to an ever-increasing amount machinery of all kinds, is one of the most direct applications of the force brought into play between an electric current and a magnetic field. But in order to obtain the current for such purposes, mechanical means are necessary, and these mechanical means find their realisation in the electric dynamo. We shall now turn our attention to the electro-magnet, that device which is fundamental to nearly all the useful appliances of the electric current, and next to the dynamo, and shall see how an important discovery due to Faraday led immediately to the possibility of constructing machines for producing electric power on a sufficiently large scale for commercial purposes.

CHAPTER II

The Electro-Magnet

STARTING with the knowledge of the direction of the magnetic field in the neighbourhood of a wire in which an electric current is flowing (p. 14), it is easily seen that if the wire makes a loop, as in Fig. 7 (*a*), the magnetic lines of force emerge from the coil on one side, travel round externally, and re-enter the coil by the other face. If the same strength of current is employed, the magnetic field will be increased by making several turns or loops to the coil (Fig. 7 (*b*)), for each turn will produce its own effect, whether the other turns are present or not. Thus the magnetic effects of the separate turns of wire must be added together to obtain the resultant magnetic effect of all the turns. Such an arrangement is commonly employed in constructing a GALVANOMETER for detecting or measuring small electric currents. If a magnetic compass needle be suspended at the centre of such a coil, the very feeble effect of a small current upon it is multiplied many times by using a considerable number of turns. In some sensitive galvanometers several thousands of turns are employed.

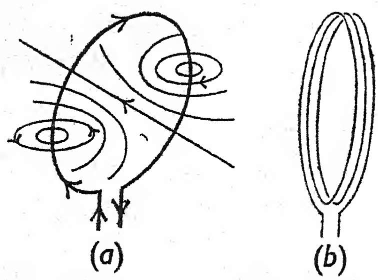


FIG. 7. Magnetic field due to an electric current in a circular coil.

Another arrangement of the coil is obtained by placing the turns side by side, as in Fig. 8, by winding the wire on a piece of tube. Such an arrangement is called a SOLENOID. The magnetic lines of force now pass through the solenoid,

emerging at one end A (Fig. 8), spreading out, and re-entering at the other end B. It was shown by Andrée M. Ampère (1823) that a solenoid with an electric current flowing in it behaves exactly like a magnet; in fact, any current circuit may be imitated in its magnetic effect by an appropriately shaped magnet. But there is this difference between a magnet and a solenoid, that whereas the magnet is solid, and its interior is inaccessible, the solenoid is hollow, and the condition of the interior can be investigated. It is not at all difficult to show, either by means of a compass needle or by means of iron filings, that the magnetic lines of force in the interior of the coil are as shown in Fig. 8.

It has already been seen (p. 9) that a piece of steel is converted into a magnet by being stroked by the pole of

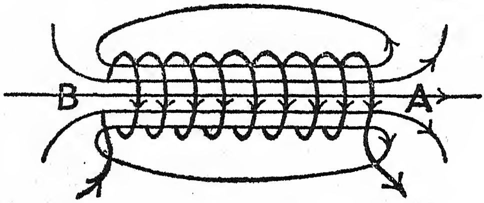


FIG. 8. Magnetic field due to a solenoid.

another magnet. The act of stroking merely brings the steel into very close proximity with the magnetic pole employed; the actual contact is in no way necessary for the magnetisation produced, which is in marked distinction to the process of electrification by friction (p. 2.) The essential condition for magnetisation is that the piece of steel shall be placed in a magnetic field. Soft iron is magnetised very easily under these conditions, but readily loses its magnetisation when withdrawn from the magnetising field. Again, if a steel magnet be broken, the parts are found to have new poles, so that each is a complete magnet having a N. and a S. pole (Fig. 9). These and other well-known facts have led to the idea that magnetisable materials—steel, iron, nickel and cobalt—consist of minute parts, each of which is always a magnet. When

the material is not magnetised these parts are set in all directions indiscriminately, as represented figuratively by the little lines to represent these magnets with arrows to show their N. poles in Fig. 10. But a magnetic field acts upon each elementary magnet just as it would upon any other magnet, causing its N. pole to point in the direction of the field and its S. pole in the opposite direction. The result is that there is now a pole at each end of the bar, one being a N. and the other a S. pole. This arrangement is illustrated in Fig. 10 (*b*), but it must be remembered that the strokes representing the elementary magnets NS are drawn enormously too large; for the actual elements are small beyond even microscopic vision. This theory of magnetisation is supported by far more evidence than can be given here. It took its rise many years ago, but was presented by Sir J. A. Ewing, who showed that all the peculiarities in the magnetic properties of iron and steel are consistent with, and can be explained by, such a theory.

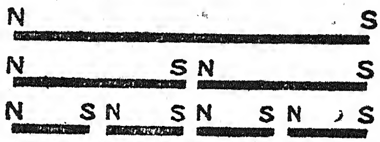


FIG. 9. Poles produced on breaking a magnet.

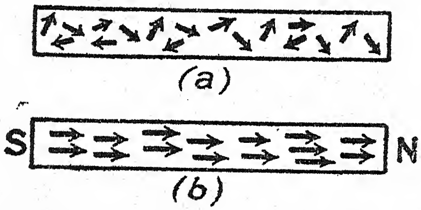


FIG. 10. Illustration of magnetisation.

Turning again to the solenoid with a current flowing in it (p. 19), the effect of putting a piece of iron inside it becomes evident. The elementary magnets of the iron turn into the direction of the magnetic field due to the current, and produce magnetic poles at N and S (Fig. 11), which are many times stronger than the poles of the solenoid without iron. It may easily happen that the pole with the iron present is a thousand times as strong as it would be with no iron present. The use of the iron core to the solenoid is, consequently, of very great importance in

practice, the variety of applications of it being innumerable. Such an arrangement of solenoid with an iron core is called an ELECTRO-MAGNET, and a few of the more direct applications of the electro-magnet will not be out of place here. Many complex appliances, such as the telephone, induction coil, etc., are dependent upon the principle of the electro-

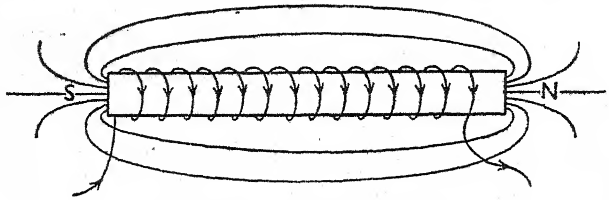


FIG. 11. Simple electro-magnet.

magnet; but there are several direct applications where little more than the electro-magnet itself is involved.

The simple straight form of the electro-magnet seen in Fig. 11 is seldom met with. When the attractive effect of its poles for iron is to be used, increased effect is obtained by applying both poles to the iron. This necessitates bending the core round so that the two poles are near together as at NS (Fig. 12), the solenoid generally being wound upon the straight limbs of the iron. Care must be taken that the winding is continuous, and where the wire passes from one limb to the other, as at AB, it must pass from front to back, or back to front, in order to ensure correct magnetisation of the limbs. The core of the electro-magnet must always be made of soft iron, never of hard steel, the reason being that hard steel will retain most of its magnetisation when the current in the windings ceases. This would be in most cases troublesome, because one of the chief advantages of an electro-magnet is that it

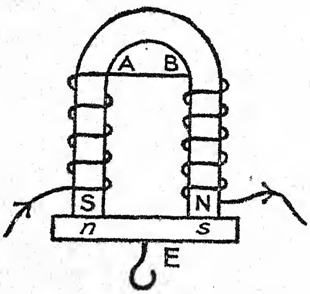


FIG. 12. Horse-shoe electro-magnet.

can be rendered active or inactive by merely starting or stopping the electric current. The pressing of a key which completes the electric circuit brings into play, by means of the electro-magnet, great forces which last only so long as the key is pressed. The soft iron bar E, known as the armature, is rendered magnetic with poles as shown. It is clear that the attractions between N and *s* and between *n* and S pull the armature on to the electro-magnet. The core may be solid or may be built up of strands of iron wire, which latter arrangement has many advantages over the solid type.

As an apparatus for lifting weights, the electro-magnet is coming more and more into use, and there are several forms for moving masses of iron from place to place. One such arrangement is seen in Fig. 13 (Plate I).

There are many other commercial purposes for which electro-magnets are employed. For example, in a simple magnetic separator used for withdrawing iron particles from other material, a travelling belt carries the mixture over an electromagnet which attracts the iron but has no effect on the rest of the material. Electro-magnets are also used in hospitals for withdrawing metal particles from the human eye.

The electric brake employed on trams is of importance, because it is very powerful and easily applied. It is nothing more than an electro-magnet carried on the body of the tram, the poles being situated immediately over the steel rail. The arrangment will be seen in Fig. 14, in which (*a*) is a side view and (*b*) an end view of the brake. When the electric current passes through the coil A the core B becomes magnetised, and since the rail acts as an armature it is strongly attracted to the poles of the core. The core is thus forced on to the rail and the friction between the two surfaces gives a very powerful braking effect. This form of brake is very effective on an incline or in an emergency, but acts too violently for ordinary use. The very gentle braking action of the electric motors

themselves is used for stopping the tram under ordinary conditions, but this will not hold the tram on an incline, where the friction brake must be applied.

Among the innumerable applications of the electro-magnet, its use in driving and controlling clocks should not be omitted. There are three distinct ways in which this has been attempted, each method having some advantages and some disadvantages with respect to the others. The first method consists in replacing the ordinary driving weight or mainspring of the clock by an electro-magnet or coil which gives an impulse to the pendulum once in each vibration. A current passes through the electro-magnet or coil when the circuit is closed by a

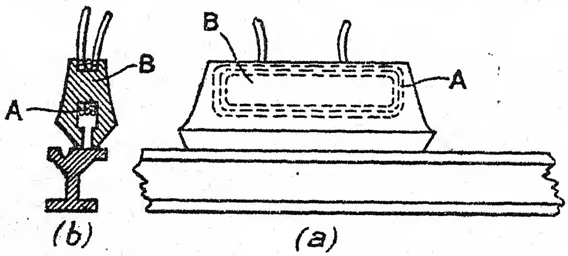


FIG. 14. Electro-magnetic brake for tram.

contact or key actuated by the pendulum. The energy for driving the clock is therefore derived from the battery which produces the current, and since batteries are somewhat unreliable, and at best require periodical changing, this method has not come into common use. In the second method a regulating or controlling circuit is supplied to a number of clocks, so that regularly timed impulses from a central control clock can affect all the clocks concerned. In some cases the impulse consists of a momentary current, which, in passing through a coil at every beat of the pendulum, forces the pendulum to keep to the time interval of the impulses. In other cases the impulse is supplied once in every hour, which by means of an electro-magnet, pulls the minute hand of the controlled clock into its

correct position. This amounts to setting the clock right once in every hour. Both these processes are known as *synchronising*, or the keeping of the independently driven clocks in time with some standard clock. The disadvantage of the method lies in the fact that if for any reason, such as temporary stoppage, the controlled clock gets badly out of time, the synchronising impulses cannot set the clock right; it must be carefully reset.

The third method is also a central control method, but is in addition a central driving method, the current being

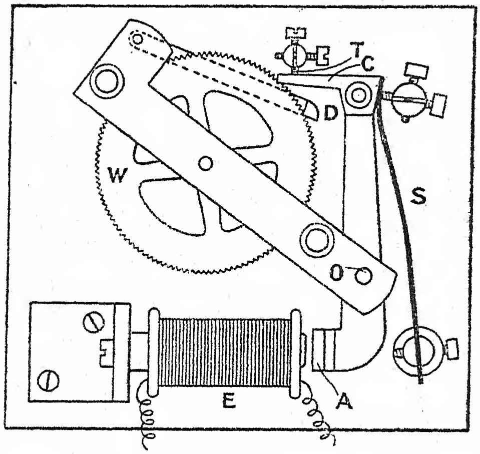


FIG. 15. Hope-Jones electric movement for clock.

supplied through electric wires to the separate clocks. Properly speaking, there is only one clock to this system, and this is situated in some central position, and regulates the sending out of short impulsive currents at frequent and regular intervals. These currents actuate an electromagnet at each of the dials at which time is to be exhibited, the electro-magnet moving the hands over the dial by an appropriate amount. There are many difficulties in performing this, but Fig. 15 illustrates a device by Mr. F. Hope-Jones which is very efficient, and is adopted by the Synchronome Co. The minute hand of the dial is attached

to a wheel W having 120 teeth. A click C is pushed forward by the spring S and drives W forward through a space of one tooth. When a momentary current from the central clock passes through the electro-magnet E, the iron armature A is attracted; this armature is carried by the same lever that carries C. The lever is pivoted at O, so that when A experiences the pull by the electro-magnet, C is withdrawn from the tooth of W, ready to be pushed forward by the spring when the impulsive current in E is over. The stop T prevents the wheel W being driven forward more than one tooth at a time. Since the impulsive currents in E arrive from the control clock once every half-second, it will be seen that the minute-hand is moved forward in correct time. The click D ensures the locking of the wheel W while the click C is withdrawn, and thus acts as a back stop. Such systems of central control for clocks are widely used on railways and for other public purposes.

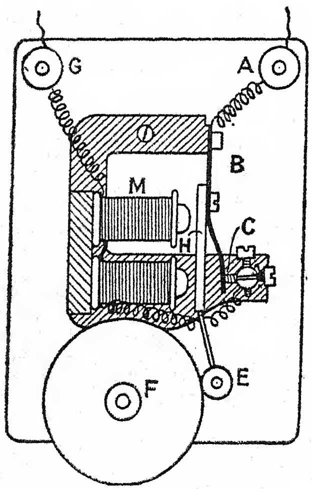


Fig. 16. Electric bell.

(The latest form of electric clock is, however, driven by synchronous motors from an alternating current circuit; see Chap. IV.)

Another simple and important example of the use of an electro-magnet is seen in the case of the common electric bell, Fig. 16. The electro-magnet M is excited by a current entering by the terminal A and passing by way of the steel spring B to the contact C, then through the coils of the magnet M, and out by way of the terminal G. The soft-iron armature H is attracted by the electro-magnet, and so the contact C is broken. It follows that the current is cut off. But interruption of the current

means that the soft iron core of the electro-magnet will cease to be magnetised, and it will no longer attract the armature H. The spring B then carries the armature back to its original position, and contact is made again at C, so that the whole process is repeated. It is therefore seen that, so long as the terminals A and G are connected to a battery, the armature H will vibrate backwards and forwards, and if it is provided with a hammer E which strikes a gong F, the bell will continue to ring. This arrangement of make and break renders the current intermittent, and is used in many cases where an automatic repeated interruption of the current is required. The rapidity with which the strokes of the hammer follow one another in the case of

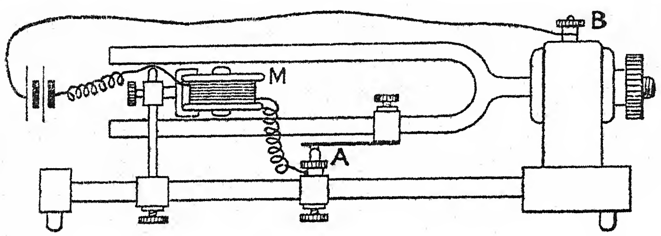


FIG. 17. Electrically driven tuning-fork.

the simple trembler of Fig. 16 depends upon the stiffness of the spring B and the weight of the hammer E; but, in this rough arrangement, the frequency of the blows is not a matter of great importance. For some purposes a rapid vibration of very constant rate is required, and a modification of the arrangement may then be made. A tuning-fork supplies the body of constant frequency of vibration, and a make-and-break device may be applied, so that the intermittent current maintains the tuning-fork in vibration, while the fork itself causes the interruption of the current. The tuning-fork being of steel, the prongs are pulled together whenever an electric current flows in the electro-magnet M (Fig. 17). The raising of the lower prong breaks the electrical contact at A, and of course the cessation of

the current allows the prongs of the fork to spring apart again. The actual terminal is not placed on the spring at A, for the connecting wire would then hinder the free motion of the tuning-fork. It is placed at B, on the heavy metal support, so that the current traverses the stand and tuning-fork itself on the way from the spring to the battery. Such an electrically driven tuning-fork provides an excellent means of maintaining an electrical current, interrupted at constant frequency, such as is employed when the mechanism of the machine telegraph is required to be driven at constant speed.

Electromagnetic devices are now used in automatic signalling. As the train passes over a section of the track, it completes a magnetic circuit: the electro-magnet is energised and attracts an armature which closes a circuit including a signal lamp. By arranging that as one circuit is closed in this way, a second circuit is opened, it is possible to cause a red lamp to light up to show that the train is on a particular section of the track, while yellow and green lamps light up to show "danger" or "all clear" for other sections.

For experimental work in which very strong magnetic fields are required, for the examination of the magnetic properties of feebly magnetic materials, an electro-magnet of special design is required. One such form of powerful electro-magnet is seen in Fig. 18. Between the tips of the pole pieces, the magnetic field is intense, and has a further property that it falls off very rapidly on proceeding away from the pole tips. This condition of a magnetic field which varies rapidly from point to point is an important one for examining the magnetic properties of certain substances. We have already seen that the three metals, iron, nickel and cobalt are vastly more magnetic than all other substances, and on this account they are said to be FERRO-MAGNETIC. But nearly all substances are magnetic to some extent. They group themselves, however, into two classes. One class comprises those substances which tend to move

from a weaker to a stronger magnetic field; these are said to be PARAMAGNETIC. A piece of a paramagnetic substance placed near the polar tips of the electro-magnet (Fig. 18) is therefore attracted into the stronger field, and a measure of its paramagnetic properties has been made by observing the force which, under definite conditions, draws it into the strongest part of the field. This method has been used by many experimenters, and in particular by Prof. P. Curie, and has also been used for the separation of slightly

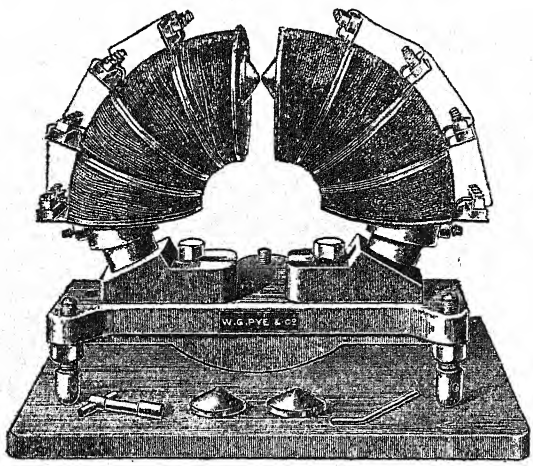


FIG. 18. Powerful electro-magnet for experimental purposes.

magnetic minerals from those which are non-magnetic. On the other hand, some substances are driven from the stronger to the weaker parts of a magnetic field and would therefore be forced away from the polar tips of the electro-magnet. Such substances are said to be DIAMAGNETIC. Amongst the paramagnetic materials we find platinum, aluminium, and many minerals containing iron, while silver, gold, bismuth, antimony, water, and sulphur are diamagnetic.

Many devices have been used for separating the different constituents of mineral ores from each other by making

use of their variation in magnetic properties. The Rowland-Wetherill separator is illustrated in Fig. 19. The crushed ore from the hopper H is fed on to an endless belt B driven by two pulleys. It passes between the poles P_1 and Q_1 of two electro-magnets and the magnetic pieces of ore are attracted to the V-shaped pole pieces P_1 where the magnetic field is intense, while the non-magnetic remainder is carried forward and delivered into the receptacle A. Two belts E and F, similar to B but moving at right angles to it, pass one under each pole, and the magnetic particles

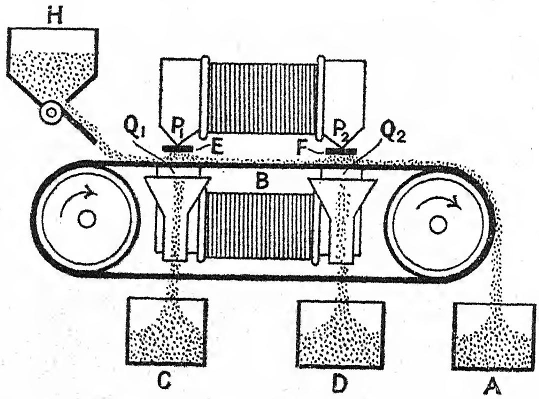


FIG. 19. Rowland-Wetherill magnetic separator.

are pulled on to the under side of the belts and are so carried out of the magnetic field and delivered into the receptacles C and D. By arranging the pole P_2 to have a greater pull than P_1, the more magnetic particles are drawn up by P_1 and delivered to C, while the stronger pole P_2 pulls up the less magnetic particles, for which P_1 was not strong enough, and these are delivered to D. Thus the arrangement constitutes a double separator, which is used to separate the three minerals, ilmenite, monazite and zircon. The zircon is delivered into the receptacle A, ilmenite into C and monazite into D.

CHAPTER III

The Dynamo

WHEN searching for a possible effect of an electric current upon neighbouring circuits, Faraday made, in 1831, a discovery of first-rate importance. It was known that a magnet caused pieces of iron or steel in its neighbourhood to become magnets, and that electrostatic charges could produce electrostatic charges on neighbouring conductors. Is there, then, a similar property for electric currents ? That is, will a current flowing in a conductor produce by its mere presence, an electrical effect in neighbouring conductors ? By no arrangement of the conductors could such an effect be produced, but in performing the experiment, Faraday discovered that *on starting* a current in a wire, a momentary current may be produced in a wire near it and parallel to it, provided that this second wire forms part of a complete conducting circuit. It is well known that if this second circuit is incomplete, no current will flow in it. When a current flows on the completion of any circuit we say that there is an ELECTROMOTIVE FORCE in the circuit. Thus an electric cell or battery such as the voltaic pile is a source of electromotive force, and in this case the chemical changes in the cell are the source of the energy which drives the current.

In Faraday's experiment it is clear that the starting of the first current produced an electromotive force in the neighbouring wire. Further, on stopping the current there is again a momentary electromotive force in the neighbouring wire, but it is in the opposite direction to the electromotive force due to the starting of the current.

Faraday soon traced these effects to the magnetic field due to the first current. This field springs into existence

on the starting of the current, and disappears on the stopping of the current, and in either case the magnetic lines of force cut across the neighbouring wire. We say, therefore, that whenever magnetic lines of force cut across a conductor, there is an electromotive force produced which will produce a current if the conductor forms part of a complete conducting circuit. These are called INDUCED currents and electromotive forces. A simple experiment will show that induced currents and electromotive forces are due to the motion of magnetic lines of force. Many turns of silk-covered copper wire are wound upon a bobbin B (Fig. 20), and the free ends of the wire are connected to a galvanometer G. The galvanometer is itself a vertical coil of wire with a pivoted magnetic needle at its centre. Any current in the coil of the galvanometer will produce a magnetic field which causes a disturbance of the suspended magnetic needle.

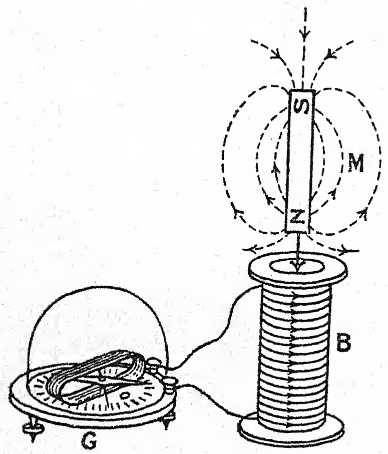


FIG. 20. Experiment representing the production of current by electro-magnetic induction.

On bringing a bar magnet towards the coil B, and allowing one pole to enter B, a deflection of the galvanometer needle will be observed for the whole time that the magnet is in motion. On withdrawing the magnet another deflection of the needle is produced in the opposite direction to the first. If the magnet remains fixed and the coil B be moved instead, the effect is the same as before, showing that the electromotive force produced is due to the fact that the magnetic lines of force and the wire of the coil cut each other, and the direction of the electromotive force

PLATE I

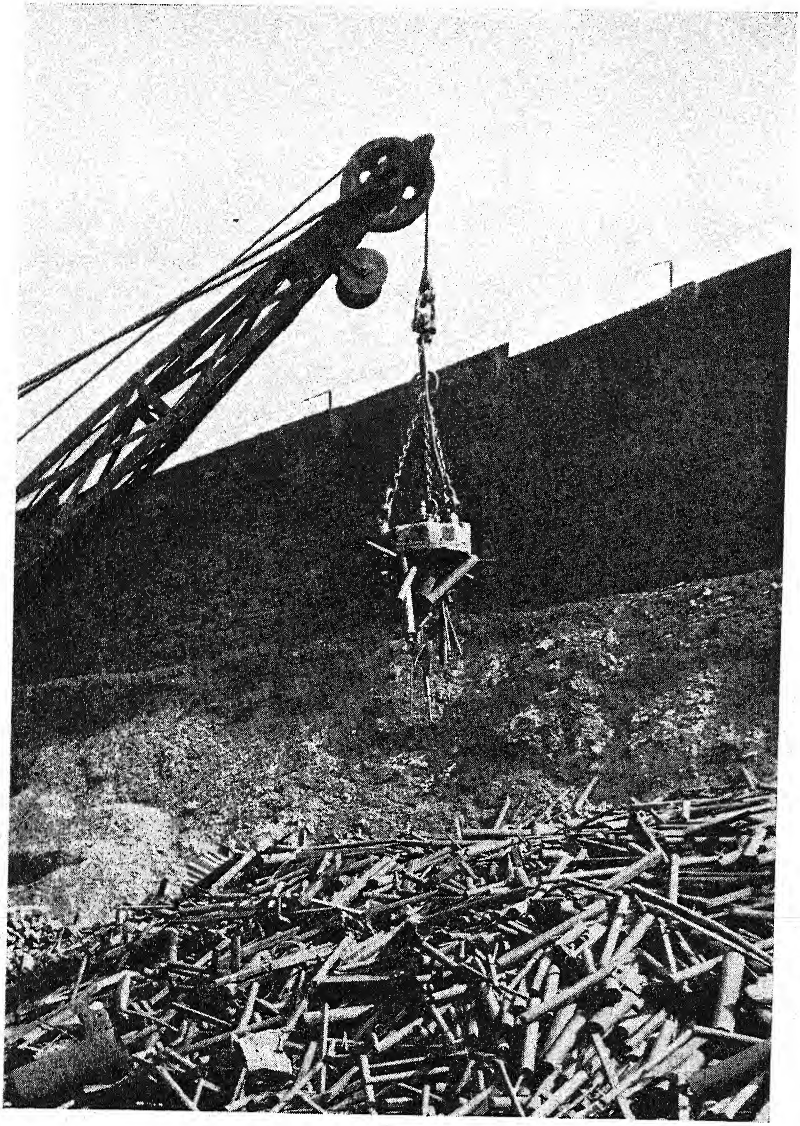


Fig. 13. Electromagnetic crane for separating and transporting iron and steel scrap

PLATE II

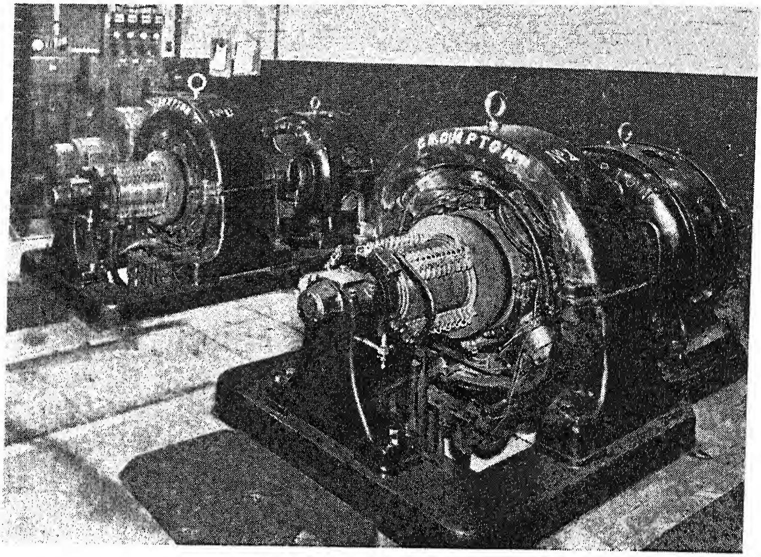


Fig. 24. Motor-generator, with front view of the four-pole direct-current dynamo

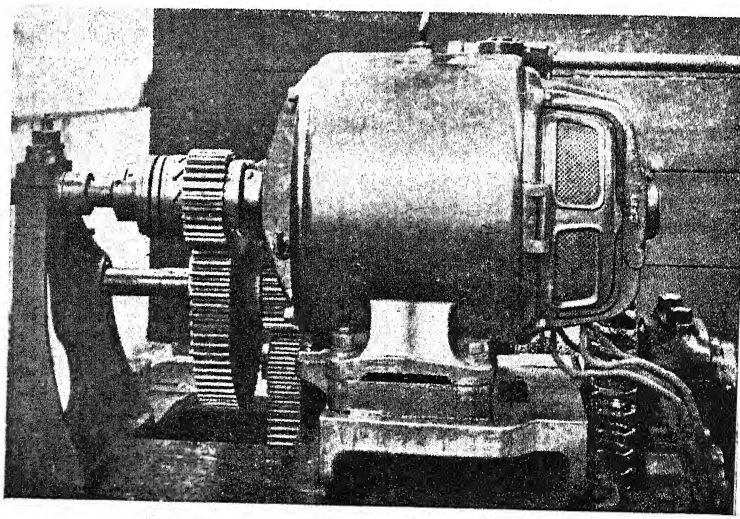


Fig. 28. 15 H.P. series motor with slip coupling to call attention to overload

depends upon the direction in which the lines cut the wires. It may also be observed that if the magnetis pushed rapidly into the coil, the deflection is greater, but of course lasts for a shorter time than when it is done slowly. Consequently the electromotive force is increased by increasing the rate at which the lines of force cut the wire, or the number of lines of force which cut the wire per second.

A simple and useful rule may also be deduced from this experiment if care be taken to note the direction of the current. This rule is that "if we look along the magnetic lines of force towards the circuit, then, if the number of lines of force passing through the circuit is *increasing*, the electromotive force acts in an *anti-clockwise* direction round the circuit; but if the number of lines passing through the circuit is *decreasing*, the electromotive force acts in a *clockwise* direction."

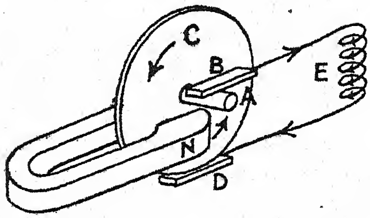


FIG. 21. Continuous production of current by electro-magnetic induction.

It now becomes clear that it is possible to obtain electric current by mechanical means, by making use of steam power to cause the motion of an electric conductor in a magnetic field.

An obvious method of attempting to make use of this effect is to mount a disc of metal, which must be a good conductor of electricity, on an axle, and to cause it to revolve rapidly in a magnetic field. If a copper disc C (Fig. 21) be mounted on an axle A, so that it can be driven round at considerable speed, and a magnet N be situated with a pole on either side of the disc, the magnetic lines of force of the magnet pass through the disc. On causing rotation, the metal cuts across these magnetic lines of force, and an electromotive force is produced in the disc. The direction of the electromotive force is at right angles both to the magnetic lines and to the direction of motion, and is therefore directed along the radius of the disc, from the

edge towards the axle. On allowing a strip of metal B to touch the axle and another strip D to touch the edge of the disc, it will be found that a current will flow in a wire E connected to B and D. This is a primitive form of dynamo, and one that was devised shortly after Faraday's discovery of induced electromotive force. It can never, however, be of any great practical use, for although fairly large currents may be produced, if the wire is of sufficiently great conductivity, the electromotive force is too small to be of any practical value. The electromotive force is proportional to the number of magnetic lines of force cut per second, and with a powerful magnet and a disc making 2000 revolutions per minute, it is probable that the electromotive force acting would be less than 1 volt, that is, it is less than the electromotive force of an ordinary cell. It is only by using a number of conductors in series, so that the electromotive force is the sum of those in the separate conductors, that a useful electromotive force can be obtained.

The general mode of doing this is to arrange the conductors, which are bars or wires of exceedingly pure copper, round the circumference of a cylinder mounted on an axle. The copper bars are connected together in such a manner that the current produced can pass through them, and out by means of a sliding contact, to the external circuit, where it is employed for some useful purpose.

Such an arrangement is shown somewhat diagrammatically in Fig. 22, and is called the ARMATURE of the dynamo. AB is one of the copper bars. These lie in the slots or grooves of an iron core, built up of stampings from iron sheet placed face to face, and keyed on to the axle. The appropriate ends of the conductors are soldered into other copper strips, shown at C, against which the brass or copper brushes D and E bear. This arrangement is called a COMMUTATOR, and the sliding contact between the brushes and the sections of the commutator enables the current to be collected and conveyed to the external circuit. F is the pulley over which the belt from the engine passes, in order

to cause the rotation required. The method of connecting the armature conductors to each other and to the commutator varies with each machine, and is too complicated to enter into here.

In order to obtain a strong magnetic field in which the armature conductors shall move, electro-magnets are employed in all large machines. These electro-magnets have various shapes, but a simple form is shown in Fig. 23. An end view of the machine, which is called a DYNAMO, is taken for simplicity. The electro-magnet or FIELD MAGNET is provided with two heavy pole pieces marked N and S, and

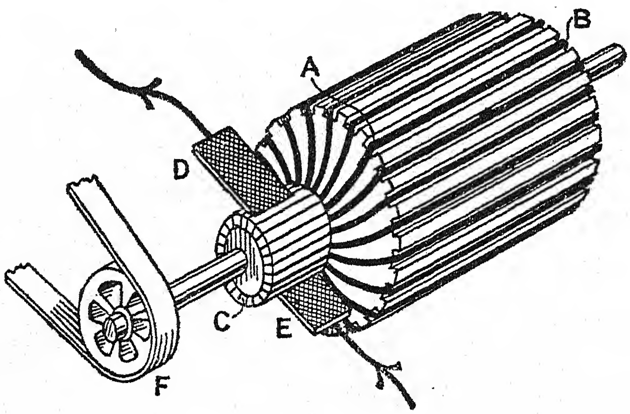


FIG. 22. Armature and commutator of a direct-current dynamo.

is magnetised by an electric current passing in the coils on the limbs A and B, bolted into a yoke C. The pole pieces, limbs, and yoke are all constructed of iron, and produce a powerful magnetic field in the cylindrical space between N and S. In this space the armature rotates, and it will be seen that all the armature conductors on the right-hand side are passing down through the magnetic field, while all those on the left-hand side are passing upwards. A method of connecting the armature conductors to the commutator is shown, and by tracing out the connections it can be seen that the current produced by the cutting of the conductors

across the magnetic field will leave the commutator by the brush D, and enter by the brush C. In Fig. 23 the current for the field magnet is the actual current produced in the armature of the dynamo, which also flows in the external circuit. The three parts of the circuit, that is, the armature, the field coils, and the external part, are said to be in SERIES, and in this case the machine is called a SERIES DYNAMO. In some cases the current from the armature divides between the field magnet and the external circuit, when the machine

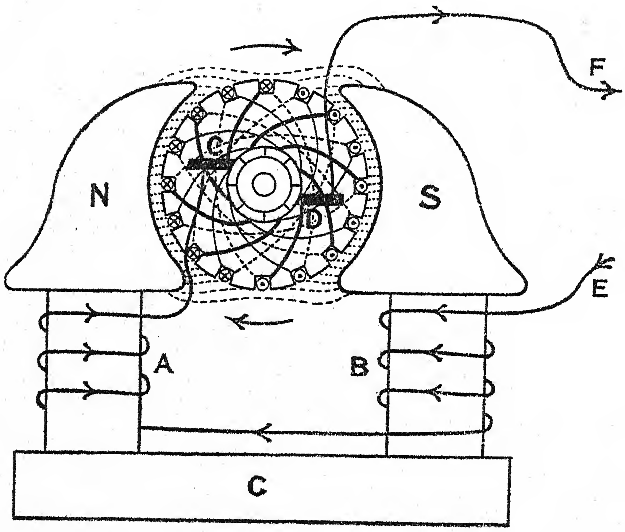


FIG. 23. Diagrammatic representation of the electrical circuits of a direct-current series-wound dynamo.

is called a SHUNT DYNAMO. Sometimes a combination of the two methods is used, when the term "compound winding" is employed.

The actual form of a dynamo will be seen in Fig. 24 (Plate II), in which the field magnet has four poles, alternately N and S; a very common arrangement. In this case the dynamo is driven by an alternating-current motor, but this in no way affects its use as a dynamo, and if driven in any other way, as, for example, by a steam engine or,

as is now a common practice, by a steam turbine, the result would be exactly the same. The pair of machines as seen in the diagram is called a MOTOR-GENERATOR, and comprises an excellent means of converting power supplied in the form of alternating current into direct current. Of course, the actual current is not converted; the alternating current is used to drive the motor, as will be explained in Chapter V, and the dynamo generates the direct current, the two armatures being mounted on the same shaft. In Fig. 24 the reader will recognise the four pole pieces, bolted to the circular iron yoke, which also forms the outer case of the machine. The brushes are of the carbon type, and three of the four sets of brush holders are clearly seen. The two motor generators shown in the diagram are in use to-day but are about twenty years old. Later types of machines are more enclosed. The stout cables at the front of the machines are for leading the current to the external circuit.

In public supply, the dynamos are driven by steam engines, or in modern stations by steam turbines, a turbine being coupled directly to each dynamo. Small dynamos are self-excited, but large ones are generally separately excited, a smaller machine being run to supply current for the field magnets of the larger, or actual supply machines. At the central supply station several large units are employed which may be connected to the main switch board or disconnected from it as the demand for current fluctuates. The current from the small dynamo which is used to supply the current for the field magnets of the large machines can be controlled by the switch-board attendant, being regulated by him in such a way that the main voltage of supply is maintained very nearly constant. If the voltage drops, owing to the station load increasing, the attendant cuts out resistance from the field current circuit, and so increases the magnetising current in the field coils of the machines, the effect of which is to raise the voltage.

The supply mains from the central station consist of well-insulated copper wires or cables, laid in conduits under the streets. The cost of these mains is very great, and when the current has to be carried some distance, the mains themselves may cost as much as the rest of the installation, including buildings, engines, and dynamos. It is therefore obvious that any method of keeping down the cost of the mains is of first-rate importance. One such method is to use as high a voltage of supply as possible; for, in order to transmit any given power, the current varies inversely as the voltage. For example, in order to transmit 100 horse-power at 100 volts, the current must be 746 amperes; but in order to transmit the same power at 200 volts, the current would be halved, that is 373 amperes.

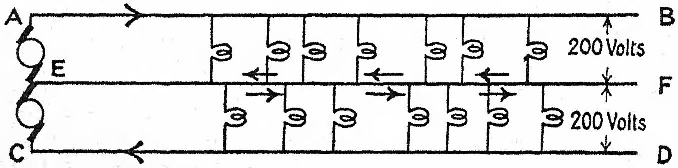


FIG. 25. Three-wire system of supply for direct current.

There is a limit, however, to the voltage used in public supply, for the danger on account of fire and electric shock to the user increases with high voltages owing to the likelihood of the insulation breaking down. The Board of Trade has therefore fixed the maximum voltage for public lighting supply at 250 volts. There is another method by which economy in mains is effected; that is by use of the THREE-WIRE SYSTEM. By using two dynamos connected to the mains as shown in Fig. 25, and employing three wires AB, CD and EF, and connecting the load across only one pair of mains, the current for one set leaves by the main AB and returns by EF. The other current leaves by EF and returns by CD. If the two loads are well balanced so that these currents are equal, it will be seen that the resultant or effective current in EF will be zero, and in any case the current in EF will only be the difference of the currents in

the two parts of the installation. Thus EF may be made of very much thinner cable than AB and CD. By placing one consumer's premises across the mains AB and EF, and the next between EF and CD, and so on, the voltage on each supply will only be, say, 200 volts, while the station voltage is 400 volts. Hence economy in mains is effected, for if the two supplies had been carried out by independent mains, four cables each as heavy as AB or CD would have been required.

A brief description of some modern developments in public supply and of the "grid system" is given in Chap. V.

CHAPTER IV

The Electric Motor

HAVING seen how Faraday's work led to the possibility of producing current by mechanical means, it is now open to us to follow the various uses of the current. Its application to the production of motive power is perhaps the most appropriate at this stage, because the electromotor is in all respects the counterpart of the dynamo. In fact their functions are reciprocal, one converting mechanical energy into energy of electrical current, and the other converting the energy back again into the mechanical form. One of the chief functions of electricity is to enable energy to be distributed economically and conveniently. Our chief source of energy is coal, whose energy is traceable to the chemical affinity of the carbon and hydrogen, of which it is chiefly composed, for the oxygen of the air. On burning the coal in furnaces, this energy becomes heat, and on being employed to boil water under pressure, the energy can be used for driving the piston of the steam engine backwards and forwards, or for causing rotation directly in the case of the steam turbine. In either case, the mechanical energy produced is employed to produce rotation of the armature of the dynamo and so the electric current arises. By far the greater part of the electric current used is produced at central stations, as its production on the large scale is much more economical than production by small electrical machines. From the central station the current is conveyed by insulated copper conductors or cables to the place at which it is to be usefully employed. Whether for lighting, heating, or power depends upon circumstances. The public supply from central stations is used commonly for all these purposes.

The advantage of using electrical power for driving machinery, trams, trains, etc., lies in the fact that the power can be supplied conveniently at the point at which it is required, without the intervention of shafting, belts, and pulleys. Also the current can be switched on and off as required. Thus there is no wastage when the machine is at rest, as is the case when a factory is driven by its own set of boilers and engines, and the shafting is always running.

The electromotor depends for its action upon the reverse effect to that of the production of a current by the motion of a conductor across a magnetic field. If an electric current flows in a conductor which is situated in a magnetic field, and at right angles to the direction of the field, as in Fig. 26, then the conductor will experience a force urging it to move at right angles to both the current and to the magnetic field. This effect can be seen at once to supply the necessary condition for constructing an electromotor. On referring to Fig. 23, it will be seen that if, instead of applying a mechanical power to cause the armature to rotate, a current be applied to the machine, entering at E, passing through the field coils B and A, it will cause the magnetisation of the field magnets as shown. Also the current will enter the armature by the brush C, pass through the armature conductors, leaving by the brush D and eventually pass out by the conductor F. Through all the conductors on the right-hand half of the armature the current is passing from back to front, and in those on the left-hand half it is passing from front to back. Reference to Fig. 26 will then show that the conductors of the right-hand side of the armature will experience a force urging

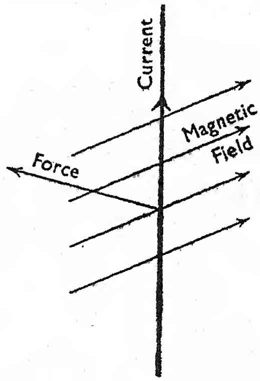


FIG. 26. Relation between current, magnetic field, and force on conductor.

them upwards, while those on the left-hand side are urged downwards. It follows that the armature is caused to rotate, but in the opposite direction to that in which it was driven when being used as a dynamo for the production of current. This would, of course, necessitate a resetting of the brushes, which have the wrong slope for the running of the machine as a motor.

The case described above is an example of the general rule, that every dynamo, when supplied with current, will run as a motor, and the direction of running when used as a motor is the reverse of that when used as a dynamo, unless of course the electrical connections are altered in any way.

An electromotor, like a dynamo, may be separately excited, series wound, shunt wound, or compound wound. For driving machinery the winding is usually shunt or compound, while for traction it is usually series.

One problem that arises in connection with the use of electric motors is particularly worthy of note. The conducting wires of the armature are of fairly low electrical resistance, so that on switching on the current from the supply mains, a very great current will flow. This is not altogether a disadvantage, for the starting of the motor, especially when under load, requires a large current; but if this large current persisted for long, the heating of the conductors through which it flows would be so great that the insulation would be burnt, and the machine would be permanently injured. Fortunately, however, there is a wonderful compensation at work, for as the speed of the motor increases, the current it takes from the mains becomes less. This at first sight seems surprising, but it is clear that when the armature is rotating, its conductors are cutting across the magnetic field produced by the field magnets. This, as we have already seen, is the condition for an electromotive force to be produced in these conductors, so that as the speed increases this electromotive force rises. By tracing out the connections in Fig 23, and

applying the rule for the direction of induced electromotive force (p. 33), it will be seen that this electromotive force acts in opposition to that in the mains which produces the driving current. This might even be deduced on general grounds, without taking the trouble to trace the various currents and forces; for if the electromotive force tended to increase the driving current, the machine would, when once started, drive itself. Hence perpetual motion would result, and useful energy would be derived from nowhere, which is contrary to experience. This back electromotive force then, limits the current taken by the motor, and the final speed is reached when the current has fallen so that just that power required to turn the armature under the given load, and provide for certain unavoidable losses, is drawn from the mains.

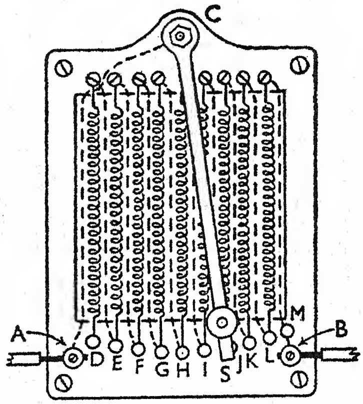


FIG. 27. Rheostat.

Nevertheless, to prevent excessive current before the motor has picked up speed, starting resistances, or rheostats, are employed with large motors. These starting resistances are merely wires of moderate resistance in the form of coils which can be cut out step by step as the speed of the armature increases. On attaining full speed, the last of the coils is cut out, the back e.m.f. produced by rotation being then sufficient to prevent the flow of a destructively large current. A simple form of starting resistance is shown in Fig. 27. In this case there are nine coils of wire stretched upon an iron frame and insulated from it. They are connected up as shown, and it will be seen that the current entering by the terminal A passes to the arm at C, and thence by the sliding contact S to one or other of the studs D, E, F, G, H, I, J, K, L, M, and out at

B. If the switch is moved so that the current passes to the contact stud D, all the coils must be traversed by the current in passing to M. But if the switch is moved over, a stud at a time, the resistances are cut out one by one, until, with the switch at M, the current passes straight across from C and B, so missing all the resistances. If such an apparatus is placed in series with the armature of a motor, the switch would be at D to begin with, and the nine resistances all being in the circuit, the current would then not be excessive. As the motor picks up speed, the back electromotive force increases, and the switch may then be moved over, step by step, until the contact stud M is reached. When the resistance is entirely removed, the back e.m.f. corresponding to full speed of the motor is attained, and the current has at no time reached an unsafe value. Starting resistances for motors are not generally as simple as the one described, although their principle is exactly the same. They are usually provided with safety devices, so that, should the field current fail, the motor is automatically switched off the mains, or if the load becomes too great, a similar operation is effected, so that injury to the motor due to over-heating is avoided.

A typical electromotor is seen in Fig. 28 (Plate II). It is a 15 h.p. series motor used for driving a machine in the Woolwich Arsenal. The method of gearing to the required amount so that the speed of driving shall be reduced from that of the motor to that required by the machine can be seen.

One of the most ingenious applications of the converse functions of the electric dynamo and motor is now employed very extensively on electric tramways and railways. This consists in making the motors which drive the tram or train also act as brakes for stopping. It has been seen that the same arrångement of field magnet, armature, and commutator will act as a dynamo and convert mechanical energy into energy of electric current when the armature is made to rotate by mechanical means, or conversely will act

as a motor and convert energy of electric current into mechanical energy when an electromotive force to maintain the current is applied to it. If all the inevitable losses due to friction, heating, etc., could be totalled up and allowed for, it is a fundamental principle that the amount of energy supplied in one form is converted to the other form. Now when the tram is in motion it possesses mechanical energy, and in order to stop the tram this energy must be got rid of. One method occurs when the tram runs up an incline, and the energy of motion does work against the weight of the tram and is so used up. Another way is to apply friction brakes, so that the mechanical energy is converted into heat. But the most refined and delicately applied method is to convert the motors into dynamos and let the tram use up its mechanical energy in driving these dynamos. All that is necessary is to disconnect the motors from the electric mains, and join their terminals together by a conductor, when they immediately act as dynamos, the energy required to drive them coming from the tram, which gradually comes to rest. In the local circuits, large currents may be produced while the speed is great, so that it may be necessary to introduce resistances to prevent this excessive current, with its destructive overheating. These resistances may be cut out step by step as the speed is reduced, so that they act in a similar but converse manner to the starting resistances of a motor. In this case the mechanical energy of the car eventually becomes heat in the armature and resistances in which the current is flowing, whereas with the friction brake the mechanical energy is directly converted into heat. The motor-dynamo or electro-magnetic brake can be very gently or very fiercely applied, according to the amount of resistance placed in the motor circuit, and it is also independent of any greasy surfaces except, of course, where the wheel touches the rail. But there is one thing it will not do, which is to hold the tram at rest on an incline; for it is only when the tram is moving that there is any braking

action. Consequently a friction brake must always be provided as an auxiliary to the electro-magnetic brake.

The controller used for an electric tram or train is of a complicated form, for it has not only to apply and cut off the motor current and put in and out the suitable resistances, but it has also to make various groupings of the motors. This last function renders the use of auxiliary resistance much more restricted than it would be if single motors connected directly across the electric supply mains were used. Suppose that four motors are used to drive the car. If these motors are all placed IN SERIES so that the same current flows through them all in turn (Fig. 29 (*a*)),

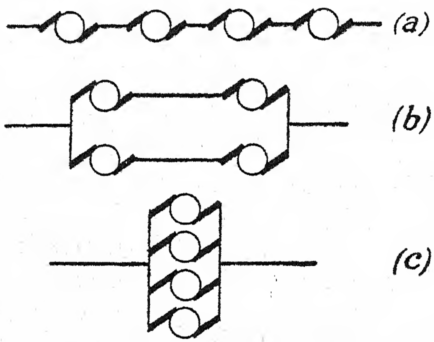


FIG. 29. Traction. Arrangement of motors for starting.

the current at the start will be only one-quarter of what it would be if one motor alone were placed across the mains. The starting current will therefore be limited to a safe amount by the resistances of the four motors in series. Now, on attaining the greatest speed of the car which this series arrangement will give, the controller changes the electrical connections to that of Fig. 29 (*b*). There is a jump up in current because only two motors are now in series, the full electromotive force being applied to the two pairs. When the speed has risen to its new limit, the controller again alters the connections to the arrangement (*c*), in which each motor experiences the full electromotive force of the supply. No injury is experienced from

excessive current because the speed reached is such that the back electromotive force prevents an unsafe current from flowing. The motors in Fig. 29 (*c*) are said to be IN PARALLEL, because the current divides, part flowing through each, the separate currents uniting again where they leave the motors. This parallel arrangement is distinctive from the series arrangement of Fig. 29 (*a*), where the same identical current flows through all the motors.

There is a very important type of electromotor which is driven by alternating currents, but the description of this is deferred to the next chapter.

One other type of electromotor must be mentioned, as it is of considerable importance. This is the motor used as a meter for measuring electric power supplied to a consumer. Power, or rate of working in any circuit, depends upon the current in the circuit and the electromotive force driving the current, and is proportional to both of these. If one ampere is maintained by an electromotive force of one volt, the rate of working, or power, is called the WATT. It follows that the power which is being expended in any circuit may be measured in watts, where—

$$\text{watts} = \text{amperes} \times \text{volts}.$$

In order to measure the watts expended in any circuit it is sometimes convenient to measure the current by means of an ammeter, and the electromotive force by means of a voltmeter and to multiply the two values together. An instrument which would do the multiplying for us so that the watts could be read directly would obviously be of great convenience. Such an instrument is called a WATTMETER, and since its principle is used in the construction of motor power meters, it will be explained briefly. An electric current produces a magnetic field, and a second current situated in this field experiences a force, as was seen on p. 41. The magnetic field of the first current may be magnified by the use of iron cores and pole pieces, as in the case of the electromotor; but even if these are absent the force will still be excited, although it

is not so great. Thus one current exerts a force upon another, and it may be found by following the various rules, that CURRENTS IN THE SAME DIRECTION ATTRACT EACH OTHER, while on the other hand CURRENTS IN OPPOSITE DIRECTIONS REPEL EACH OTHER. This is made use of in various forms of wattmeter, the Kelvin type shown diagrammatically in Fig. 30 being one of the most satisfactory. If the power in the lamp L is to be measured, the current through it is taken also through four fixed coils A, B, C, and D. The two coils E and F are connected to the lamp terminals, and the current in them is therefore proportional to the electromotive force which drives the current through the lamp. Now E and C, A and F are wound so that the currents all flow in the same direction, and attractions

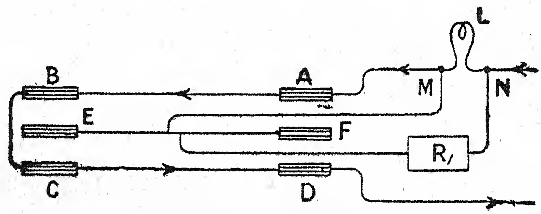


FIG. 30. Kelvin watt-meter.

between the coils result, while B and D are in the opposite direction, so that B pushes E downwards and D pushes F upwards. E and F are carried on a balance arm pivoted midway between them, so that the balance is tilted on account of the forces between the coils. The balance is restored to its original position by a weight which can be moved in manner similar to that on a common steel-yard, and the movement of this weight measures the force between the coils. These forces are each proportional to the current in L and to the electromotive force driving this current, and therefore to the watts being expended in L. The scale of the balance is therefore marked in divisions corresponding to watts, and the instrument thus forms a convenient watt-meter or watt-balance.

The rotation of the arm of the watt-meter being prevented

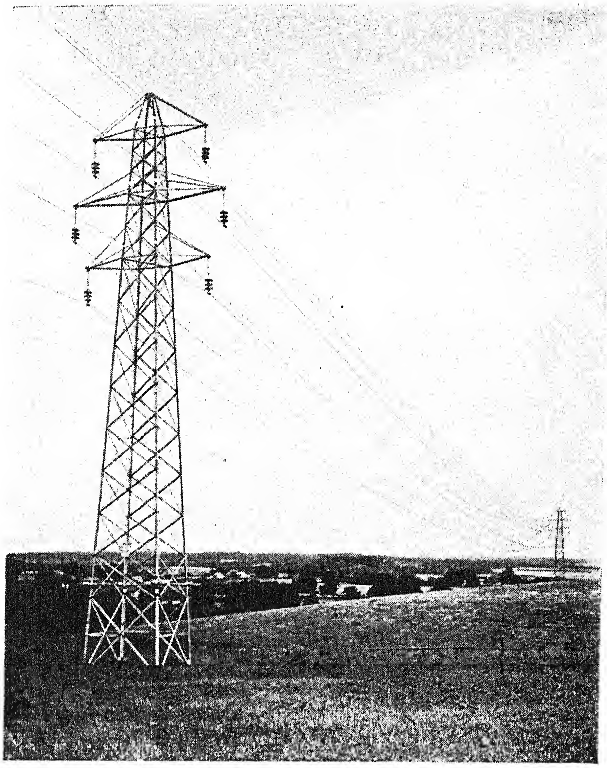


Fig. 40. Electric Pylon

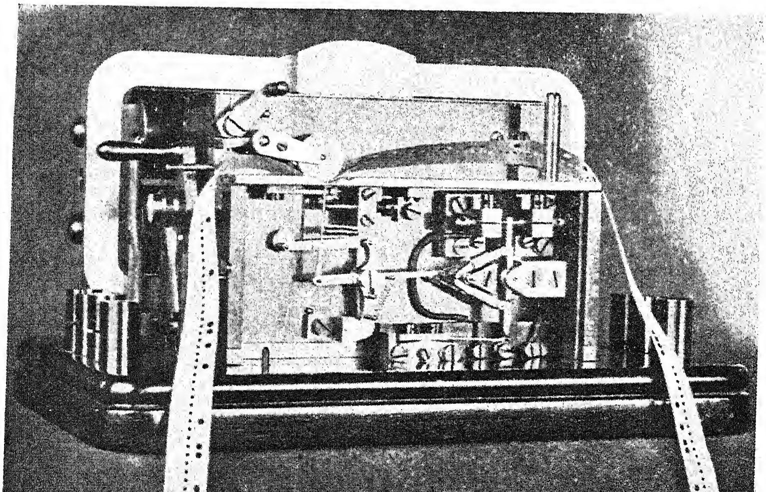


Fig. 65. Single-line Murray transmitter

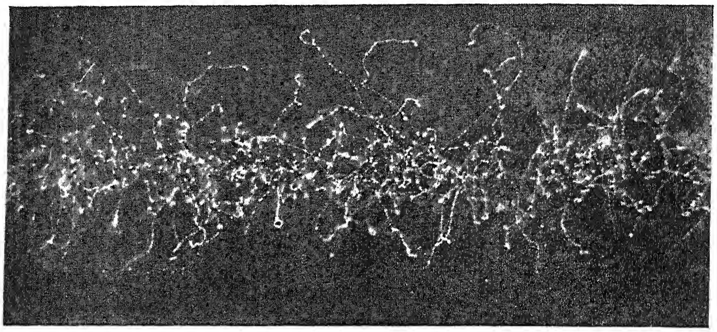


Fig. 122. (*a*) Photograph by C. T. R. Wilson of the path of a beam of X-rays through air supersaturated with water vapour, showing the cathode or β-ray tracks produced. Magnification $2\frac{1}{2}$ diameters

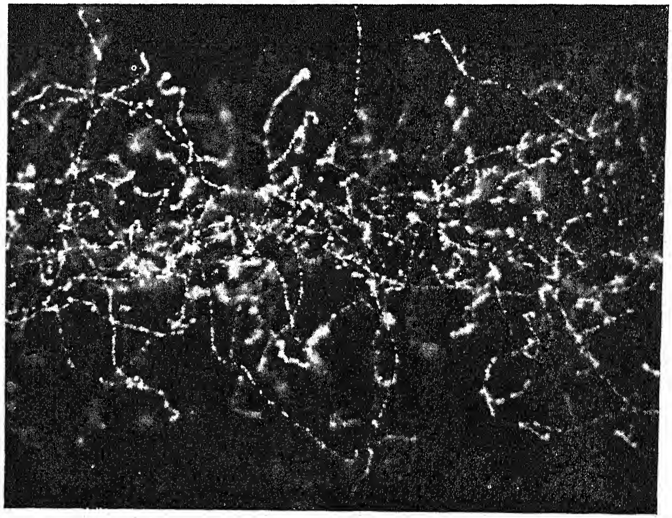


Fig. 122. (*b*) Photograph by C. T. R. Wilson of the path of a beam of X-rays in air supersaturated with moisture. Magnification 6 diameters

by the balancing weight, continuous rotation is impossible. If, however, the moving coils were designed for continuous rotation, as in the case of the electric motor, and provided with a commutator, the fixed coils would act as field coils, and the driving effect is proportional to the watts used in the circuit. If, further, the motor is arranged so that its speed is proportional to the driving force, the total number of revolutions made by the armature will be proportional to the watts and to the time for which the power is supplied. Since the power of 1000 watts continued for an hour is the Board of Trade unit, the KILOWATT-HOUR, the meter may be so provided with indicators that the kilowatt-hours supplied will be read directly. There are many designs of electric motor meter, but the principle of them all is shown in Fig. 31. The current through the load, represented by the lamp L, passes through the field coils FF, and the armature A is connected, through the commutator and brushes B, to the two ends of the load circuit, and plays the part of the movable coils of the watt-meter. It follows that the driving force is proportional to the watts to be measured. The speed of the motor is made proportional to the driving force by means of the electro-magnetic brake. A copper disc D, mounted on the motor axle, moves in the magnetic field of two permanent magnets MM, and these tend to check the motion (see p. 69), the speed being rendered proportional to the driving force. It is only necessary to add a revolution counter C, which consists of a number of dials with pointers, driven by the motor axle. The scales are added and indicate the numbers of kilowatt-hours used in tenths, units, tens, hundreds, etc.

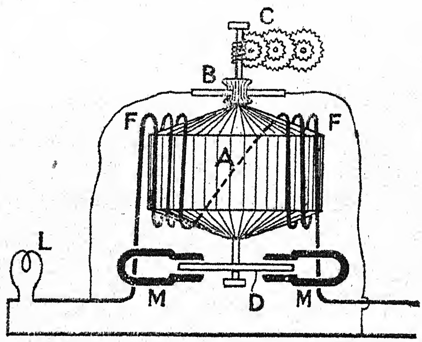


FIG. 31. Electromotor type of power meter.

CHAPTER V

Alternating Currents

THE growth of the use of electric power for industrial purposes is necessarily intimately connected with the question of cost. It is hardly likely that the distribution of power by means of continuous current could ever become economical, because the use of small dynamos, supplying current to a limited area, is extravagant. The difficulty is not got over by building large dynamos to supply considerable areas, for with increasing distance to which the current is to be conveyed, the cost of the copper mains required to carry it runs up with great rapidity, and becomes such a large proportion of the whole cost of the undertaking that the use of continuous current is severely limited.

By continuous or direct current is meant an electric current which flows always in one direction, in distinction to a current which flows alternately backwards and forwards through the conductor. If we refer again to Fig. 23. (p. 36), and pick upon any two of the armature conductors which are diametrically opposite each other, we see that in the one which is descending, the induced current is from back to front, while in the other one, which is ascending, the induced current is from front to back. Consider these two conductors to be the sides of a loop of wire, completed by joining them together at the ends. The conductor which is descending experiences an electromotive force from back to front, and as the two change positions every half-revolution we see that in a loop of wire rotating in a magnetic field is developed an electromotive force which alternately acts round the coil in the two directions. For half a rotation it acts one way round the coil, and for the

next half-rotation it acts the opposite way round. Such a one is called an ALTERNATING ELECTROMOTIVE FORCE, and if the ends of the wire are applied to an external conductor, an ALTERNATING CURRENT will flow in it (also see Fig. 38). In public supply, the number of alternations, or complete cycles of change per second, varies from 25 to 100, but the frequency most commonly employed is 50 cycles per second.

In order to transmit electrical power economically over great distances, the conductors must be made of high-conductivity copper, and must be of such a thickness that the heat produced in them, which of course means wasted power, is as small as possible. Since the heat produced per second in a given conductor is proportional to the square of the current, it follows that the cost of copper required to avoid this loss also varies as the square of the current. Thus, if we imagine the current in a given case to be trebled, the conductor carrying it must be made of nine times the area of cross section, in order to keep the waste due to heating to the same amount as before. This consideration, together with the allowance to be made as the distance of transmission increases, shows us that any method which will keep down the current, while transmitting equal power, must of course be economical. Now:

$$\text{power} = \text{current} \times \text{electromotive force},$$

so that by using a high electromotive force, the current can be reduced, while transmitting the same power. As an example, consider the case of a dynamo supplying 1000 amperes at 100 volts; the power is $1000 \times 100 = 100{,}000$ watts. But if the current were reduced to 100 amperes and the electromotive force increased to 1000 volts the power would still be 100,000 watts, but the current has been reduced to $\frac{1}{10}$ of its original value, so that the copper mains may be reduced to $\frac{1}{100}$ of their original weight for the same amount of power as before to be wasted in heating the mains. If the distance of transmission is, say, 100 miles, the saving in the high voltage arrangement is enormous;

but the difficulty arises that 1000 volts is too high for the safety of the users of the current. The risk from shock and from leakage is considerable at 1000 volts; in fact, the Board of Trade will not allow 250 volts to be exceeded. There is still the possibility of employing separate motors and dynamos locally, the motors taking current at 1000 volts and being coupled to dynamos which produce current at 100 volts. The use of substations of this kind partially solves the difficulty, but it must be borne in mind that such motors and dynamos require constant attention, the cost of which must be set off against the saving of copper in the mains.

It was to solve this problem that the ALTERNATING-CURRENT TRANSFORMER was developed. From the time of Faraday and Henry the possibility of producing a varying current from another varying current was recognised, but the use of the alternating current was not perfected for many years. The early attempts had no such definite object in view as the distribution of electric power, but were merely devices for getting momentarily very high electromotive forces from a supply of low electromotive force, such as a few galvanic cells. In this case the apparatus is called an INDUCTION COIL, but as it is the prototype of the alternating-current transformer, it is as well to consider it first.

Referring to Fig. 20, p. 32, it was seen that on passing a magnet into a solenoidal coil, an electromotive force is produced in the coil. Again, in Fig. 8, p. 20, it is seen that a current flowing in a solenoid is to all intents and purposes a magnet. Combining these two facts, it follows that if the magnet of Fig. 20 be replaced by a solenoid A (Fig. 32) in which a current is flowing, the effect on the galvanometer G connected to the solenoid B will be the same as before. That is, on pushing A into B, there is a momentary current in B and G in one direction, and on withdrawing A there is a momentary current in B and G in the opposite direction. A further advance can now be

made by keeping the coil A inside the coil B, and starting the current in A by completing its circuit. The momentary current in B and G is exactly the same as that produced by introducing A when its current was flowing. Also, on stopping the current in A by breaking its circuit, there is a momentary current in B and G exactly like that produced by withdrawing A. Thus it does not matter how the current in A is produced and withdrawn, the effect is exactly the same whatever the method. Since the momentary currents are really produced by the magnetic fields being introduced and withdrawn, it follows that anything which increases the magnetic field will increase the effect. This may be shown by using a stronger current in A, but more effectively by introducing an iron rod or core lying along the axis of the two coils. If, in addition, B consists of many windings, the galvanometer G may be dispensed with, and the wires held in the hand, when a shock will be felt on starting or stopping the current in A; or if the ends of the circuit B are near to each other, the electromotive force produced in B when the current in A is interrupted may be sufficiently great to cause the current to jump the air-gap, producing a spark. The coil A, in which the current from the battery flows, is called the PRIMARY COIL, and B, the coil in which the induced electromotive force is produced, is called the SECONDARY COIL. It is of interest to note that the original experiment of Faraday, by which he discovered the occurrence of induced currents, was of this type. Two coils of wire were wound on an iron ring, and Faraday found that on starting or stopping a current in one of the circuits, a galvanometer in the other circuit indicated a momentary current.

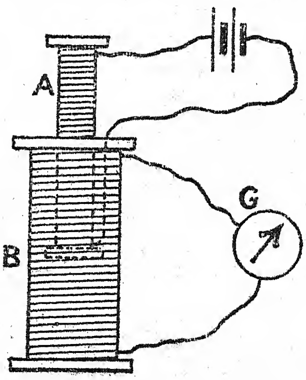


FIG. 32. Experiment to illustrate the inductive effect of one circuit upon another.

Although modern induction coils differ much in design from the simple apparatus of Fig. 32, yet there is no essential difference between them, but certain accessories are added in order to obtain more efficient working. An induction coil is shown in section in Fig. 33, in which the primary coil A and the secondary coil B will be easily recognised. The primary coil consists of a few layers of thick wire wound upon the iron core C, which is a bundle of soft-iron wires. Owing to the fact that the induction coil is intended to produce enormously high electromotive force, the secondary coil has a very great number of turns;

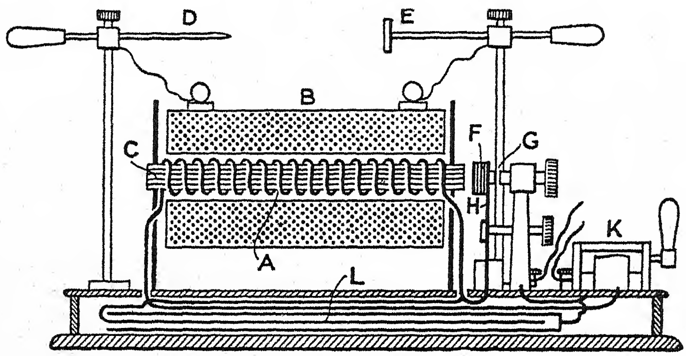


FIG. 33. Induction coil, showing the electric circuits.

since the magnetic field produced in the iron core by the primary cuts every turn of the secondary coil during the process of magnetisation, and again in the opposite sense when the iron core is demagnetised. Sparking terminals D and E are connected to the ends of the secondary coil, and between these terminals a spark in air may occur whenever the electromotive force produced in the secondary coil has a sufficiently high value. In the largest induction coils, the secondary coil is made by winding as much as 100 to 200 miles of fine wire over the primary coil. The method of making and breaking the primary circuit automatically is worthy of note, as the same method is employed in connection with electric bells and buzzers

(p. 26). A knob F of soft iron, carried by a spring H, is attracted by the soft-iron core when this is magnetised. It is therefore pulled forward, and so breaks the contact at G, causing interruption of the primary current, with consequent demagnetisation of the core. As the attraction between the core and the soft-iron knob ceases, the spring brings the knob back to its old position, and makes contact again at G, and the process is then repeated. K is a reversing key for changing the direction of the current in the primary coil as required. The only remaining part of the apparatus to describe is the CONDENSER L. It consists of layers of tinfoil separated by paper which has been soaked in melted paraffin wax. This condenser is connected across the spark gap G. Its function is complicated, but it undoubtedly increases very much the length of spark obtainable from the coil, and also lessens the destruction of the platinum-faced contacts at G.

One point in connection with the induction coil is worthy of note: a high electromotive force occurs in the secondary coil in one direction when the primary current starts, and again in the opposite direction when the primary current ceases. It might at first sight be expected that these opposite electromotive forces would be equal in value; but this is not the case, because the primary current dies away much more quickly than it grows. Since the magnetic field therefore collapses much more quickly than it grows, the rate at which the magnetic lines of force cut the secondary coil is much greater on the " break " of the primary circuit than at the "make." The "break" electromotive force is generally sufficiently high for the spark to jump the air gap DE, while the "make" electromotive force is insufficient, so that the current in the secondary circuit only flows in one direction, namely, that corresponding to the break of the primary circuit.

With a moderately large induction coil, an air gap of 20 centimetres may be jumped, and if insulating layers such as sheets of glass be interposed between the secondary

terminals they may be pierced by the spark. The crackling noise made by a long spark is characteristic of it, and the appearance closely resembles a flash of lightning on a very small scale, which in fact it is. For producing the high electromotive force required for the production of X-rays and also for the discharge necessary for production of waves for wireless telegraphy, the induction coil has had an extended and important use.

Early attempts to use the induction coil for the production of current for electric lighting resulted in failure until it was suggested that instead of using batteries and an automatic interrupter for the production and breaking of the primary current, an alternating current should be employed. Many difficulties had to be surmounted, but in the year 1883 several partially successful attempts were made to distribute electric current by this means, and in 1885 the lighting at the Inventions Exhibition at South Kensington was carried out in this way. Alternating current at 1000 volts was led to transformers, where it was converted to current at 100 volts, and so led to the electric lamps. There is no essential difference between an induction coil and an alternating-current transformer, although the names have by usage become applied to different classes of apparatus. The induction coil is used for production of very high electromotive force by repeatedly interrupting a direct current from a few cells as in the apparatus shown in Fig. 33; but when an alternating current flows in the primary circuit, and produces an alternating electromotive force in the secondary circuit, which may be higher or lower than that in the primary circuit, the name TRANSFORMER is applied. If the voltage is raised, the apparatus is called a STEP-UP TRANSFORMER, if lowered, it is a STEP-DOWN TRANSFORMER.

For a proper understanding of the mode of action of an alternating-current transformer consider Fig. 34, in which the primary current is supposed to be plotted in the form of a curve. Thus from A to B the current is increasing,

and from B to C it is diminishing, reaching zero at C. From C to D it is growing in the reverse direction to the former, and from D to E it is diminishing again to zero. After this the values are repeated for the next cycle, and so on. The magnetic field in the iron core very nearly corresponds at each instant to the primary current, so that from A to B it is increasing, and is therefore cutting the secondary circuit, and produces an electromotive force in it. At B the magnetic field has, for an instant, ceased to change, and the secondary electromotive force is zero. The dotted curve shows the electromotive force in the secondary circuit, which, of course, is zero at B, D, etc., and is greatest at A, C, E, etc., where the magnetic field is changing

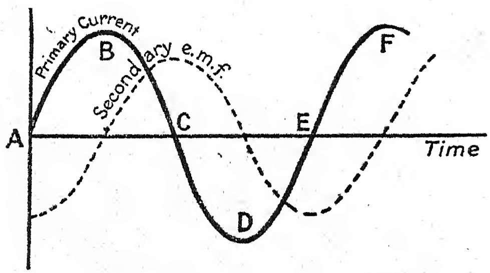


FIG. 34. Current and e.m.f. curves.

most rapidly. It is in one direction from B to D, in the opposite from D to F. Consequently, if the circuit of the secondary coil be completed through an external conductor, such as a set of incandescent lamps, an alternating current will flow in this circuit. When a secondary current flows, this complicates the determination of the magnetisation of the iron core, but the above simple consideration shows how alternating currents may be produced in the secondary circuit.

The electromotive force produced in the secondary coil of the transformer depends upon the amount of magnetisation of the core, and also upon the number of turns in the secondary coil. With a great many turns, which in consequence of its length and the smallness of its diameter

will have considerable resistance, a high electromotive force and small current will be available. But with few turns of thick wire, a small electromotive force and large current will be obtained. Thus, by choosing the number of turns in the two coils, a step-up or a step-down transformer may be produced. As a general rule the following relation is nearly true, although, of course, it cannot apply under all conditions of working:—

$$\frac{\text{Electromotive force in Secondary}}{\text{Electromotive force in Primary}} = \frac{\text{Number of turns in Secondary}}{\text{Number of turns in Primary}}$$

Transformers are made in many designs, two of which are shown in Figs. 35 and 36. Fig. 35 is a diagram of a

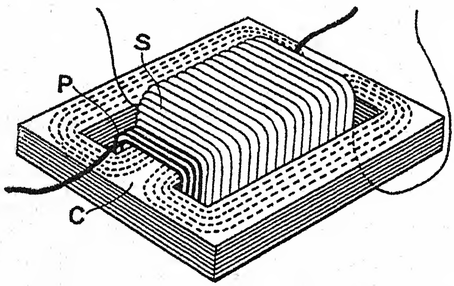


FIG. 35. Simple transformer for alternating currents.

transformer, showing the iron core built up of laminæ of sheet iron, the thick wire coil P being wound on the core, and the long thin wire coil S outside P. This is known as a closed-core transformer because the magnetic lines of force lie entirely in iron (shown by dotted lines), as distinct from the open-core transformer, in which the lines run partly in air. The induction coil is an example of an open-core transformer. When used as a step-up transformer, P is used as the primary coil, the alternating current supplied being of low voltage, and S is the secondary coil, in which a high voltage is produced. If the supply is at high

voltage, S is used as primary coil, and the low-voltage current is taken from the secondary coil P. In Fig. 36 is seen a transformer, such as is used in a substation for electrical supply. The current at the central station is produced at 11,000 volts which is stepped up to 132,000 volts and fed into the main transmission system. It is tapped off from this system and finally passes through transformers in local substations for supply to houses or shops at 230 volts. A number of transformers may be grouped together in the substation, their secondary coils being connected to "bus" bars, from which the consumers' supply is drawn. Owing to the continuous heating which occurs on account of the currents in the primary and secondary coils, and to the reversals of magnetisation of the iron core, arrangements for cooling are necessary in large transformers. In Fig. 36, the case A contains oil, which also aids in the insulation, and cold water is circulated in the pipes B, which cause circulation of the oil, and so prevent overheating.

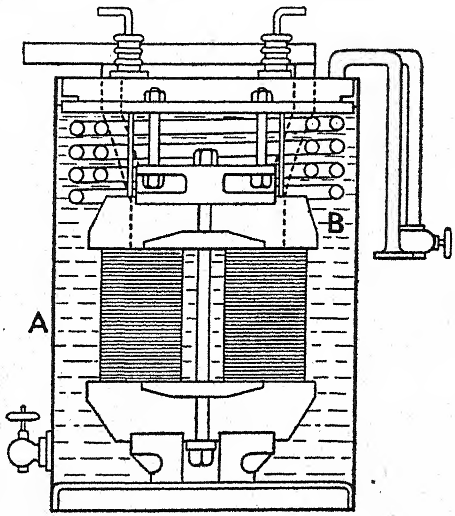


FIG. 36. Oil-bath transformer for large currents.

One of the most useful applications of the transformer is seen in the process of electric welding. Very few metals can be welded by the ordinary process of heating, placing the parts to be welded together and hammering while hot. Wrought iron can be treated in this way, but even then the process is tedious, and the welded part is never so strong as the original metal. In 1886 Prof. Elihu Thomson

originated the process of electric welding by placing together the metal parts to be welded, and passing a strong electric current through them, so that it flows across the point of contact. The resistance of the contact being greater than that of the rest of the circuit, most of the heat is produced there, and by using sufficient current, the metal at the two sides of the joint becomes melted, and the two parts fuse together. A small amount of borax is usually placed on the joint to act as a flux by removing the oxide formed at the high temperature. Even when contact at the molten place is established, the higher resistance of the hotter parts localises the heating so that melting only occurs near the joint. It is possible to use continuous current for welding, but this requires a specially built dynamo of low armature resistance, to carry the heavy current required. But the alternating current has several advantages over direct current. One form of transformer for welding, devised by Prof. Elihu Thomson, is illustrated in Fig. 37. The primary coil P has many turns, and is fed with alternating current at moderately high voltage. The secondary S is a stout circle of copper, ending in two clamps, which carry the bars to be welded together. This secondary circuit has a resistance of about 0·00003 ohm, and carries a current of the order of 10,000 amperes. It follows, of course, that the e.m.f. in this secondary circuit is of the order of one-third of a volt. A switch in the primary circuit enables the current to be applied just for

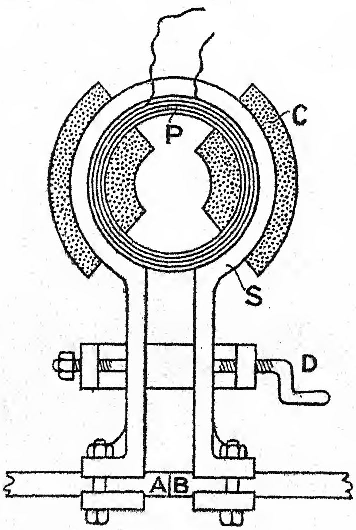


FIG. 37. Transformer for welding by means of alternating current.

the small time required for the welding. When the surfaces at AB soften, they are pressed together by turning the screw D. The magnetic part of the transformer can hardly be called the core, although it plays a similar part to the ordinary core, because it consists of a quantity of iron wire C wound upon the primary and secondary coils.

It is possible to weld most metals by the electric process; thus cast iron to cast iron, brass to brass, copper to copper, are some of the pairs successfully welded. Even such unlikely pairs as brass to iron, tin to zinc, and silver to platinum have been welded. To weld two pieces of iron rod, each 1 inch in diameter, a current of about 5000 amperes flowing for 20 seconds is necessary. Lengths of steel wire may be welded to form a continuous length, and if the slight enlargement produced at the weld is trimmed off with an emery wheel, the joint can hardly be detected, and is as strong as the rest of the wire. One very interesting application of electric welding is seen in the welding of the links of a chain. It would be thought that the current would pass through the low resistance of the complete part of the link rather than through the join. This, however, is not the case, because the rapidly alternating magnetic field through the complete circuit of the link has the effect of producing electromotive forces which oppose the current, and give this part of the link a high apparent resistance, so that the greater part of the current flows through the join, and effects the welding. This effect may be greatly increased by putting a piece of iron through the links at the moment of welding. This increases to a great extent the magnetic effect, with lessening of the current in the complete part of the link.

The development of the alternating-current transformer rendered necessary a corresponding development in the dynamo of the alternating-current form. The modern alternating-current dynamo is developed from the simple rotating coil. A single rectangular coil of wire, ABCD

(Fig. 38), rotating in a magnetic field will have an alternating electromotive force developed in it. The electrical conditions only are shown in Fig. 38, the mechanical conditions being omitted. One end of the coil, say A, is connected to the brass ring F, mounted on the same axle as the coil, the other end D being connected to E. In the position shown AB is descending, and the electromotive force produced by cutting across the magnetic field is in the direction AB. The electromotive force in CD acts from C to D, so that if the external circuit is complete, a current flows from the brush G to the brush H through this external circuit. During the next half revolution, the current flows in the opposite direction in the external

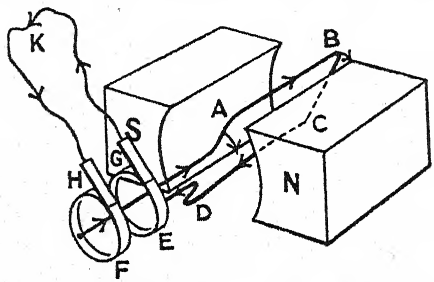


FIG. 38. Simple alternator. Diagrammatic.

circuit, so that with continuous rotation the external current is alternating, and will be of the type shown in Fig. 34, p. 57. This simple arrangment is of little use in practice, as the rate of rotation of the coil would have to be prohibitively great if a practicable voltage is to be produced. A further consideration shows that the number of cycles of current per second is too small for ordinary use when a single coil is employed. An alternating current flowing in an arc lamp produces the arc twice in each cycle of electromotive force, once with each carbon as positive. Hence the light emitted by the arc lamp fluctuates in intensity, reaching a maximum twice as many times per second as there are cycles of electromotive force produced by the alternator. The same condition applies to an incandescent

lamp, although the fluctuations in luminosity are not so great as in the case of the arc, because the filament has not time to become cold between the successive maxima of current. If the fluctuations in intensity of illumination are less than twenty per second, the effect is very distressing, as the eye perceives the flickering; but with a greater frequency than twenty per second the illumination appears to be continuous, provided that the objects seen are at rest. When the object seen by such illumination is moving, it is more brightly illuminated at successive instants of time than during the intervening periods, so that it is seen in a number of positions instead of appearing to have continuous motion. This effect may be observed very easily by swinging a walking stick when illuminated by alternating-current arc lamps, or even in incandescent lamp illumination, when the stick in several positions will be seen. For these reasons it is necessary that the alternating current should have a frequency of fifty or more cycles per second. The alternating-current generator is therefore provided with a number of coils ranged round a circle in the manner illustrated in Fig. 39. The poles of the field magnet are marked N and S, and are arranged so that N and S poles alternate. With the arrangement shown there are six pairs of poles, but in practice there may be many more. There are twelve armature coils, A, B, C, etc., and these are arranged in series with each other, and with the external circuit R by way of the slip rings and brushes PQ. The armature coils are each represented in the diagram by a single turn. This is only for simplicity, and it will of course be understood that in an actual machine each coil may have many turns. In the position shown it will be seen that the coils A, C, E, G, I, and K, are each approaching a N pole of the field magnet, and there is consequently an electromotive force in the same direction through all these coils. B,D,F, H, J, and L are at the same instant approaching S poles, so that the electromotive force in them is in the reverse direction with respect to that in A, C, etc. But the coils B, D,

etc., are wound in the reverse direction to A, C, etc., with the result that, with respect to the armature circuit, the electromotive forces in all the coils act at any one instant in the same direction. Also the whole electromotive force is reversed as the coils pass from one kind of magnetic pole to the other, and the electromotive force of the machine makes a complete cycle while the armature moves through the space of two pole pieces, so that the coil A occupies the position C, and so on. One complete rotation of the

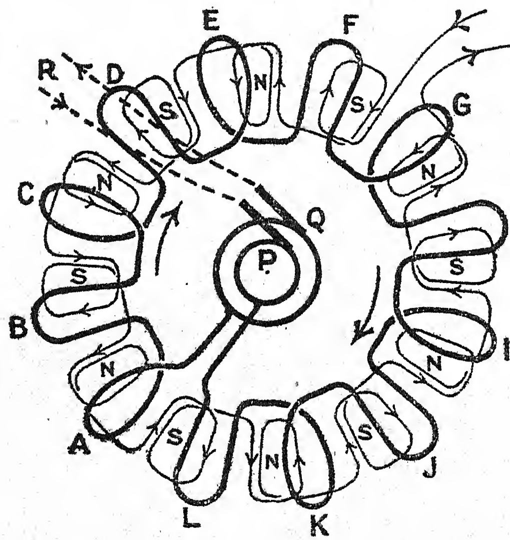


FIG. 39. Circuits of 12-pole alternator.

armature will therefore correspond to 6 cycles of electromotive force. In other words, the number of cycles of electromotive force per second is equal to the number of revolutions per second of the armature, multiplied by the number of pairs of poles in the field magnet.

It will have been noticed that the pole pieces retain their position and polarity throughout. This necessitates a constant current in the windings of the field magnets, which constant current must be supplied by a direct-current

dynamo. It follows that an alternator cannot be self-exciting, but requires an auxiliary dynamo for the production of the current for exciting the field magnets. This has one advantage, for it is possible to regulate the strength of the magnetic field by controlling the current by means of a rheostat in the direct-current circuit. In central-station practice the switch-board attendant, on observing a drop in voltage of the alternating-current supply, would increase the field current until the supply is brought back to its normal value.

There is a symmetry about an alternator which is not found in the case of the direct-current dynamo. An examination of Fig. 39 will show that it is immaterial whether the armature rotates and the field magnet is fixed, or whether the armature is fixed, and the field magnet rotates. In the latter case the slip rings must be placed in the field magnet circuit. Whichever of the two parts is fixed is usually called the STATOR, and the moving part is called the ROTOR.

The alternator and the alternating-current transformer have between them enabled natural sources of energy to be tapped which would otherwise have continued to run to waste. Among such sources are the waterfalls and rivers, where a large quantity of water falls through a considerable difference in level. Conspicuously amongst these are the Niagara Falls, the rivers of Norway, of Switzerland, and of New Zealand. Alternators driven by water turbines produce alternating current at very high voltage. This may be as high as 200,000 volts, and necessitates great precautions in carrying the current across distances of country amounting to hundreds of miles. The insulation of the cables, which are usually carried overhead on special pillars, is a matter of considerable difficulty, and presents many awkward problems to the electrical engineer. The discharge which takes place into the atmosphere at such high voltages is the cause, in many cases, of considerable loss of energy, but the saving in the cost of mains, which

would be necessary to carry the larger current at lower voltage, and the fact that the actual energy is supplied by nature, render many such schemes practicable.

In this country, electrical energy is mainly derived from coal, which is used to raise steam for driving steam turbines; these in turn drive electric generators. There are a number of power stations throughout the country where electricity is produced in this way, the largest being at Battersea Power Station, which is designed to generate up to 500,000 kilowatts. The voltage generated is "stepped up" through a power transformer to 132,000 volts, and this is carried throughout the country by overhead cables mounted on large supporting towers. The towers have to be specially designed to bear the heavy weight of the span of the wires, which for example exceeds 3,000 ft. across the Thames. The voltage must be reduced before the consumer can use it: this is done through a substation which consists essentially of a step-down transformer for reducing the voltage to 230 volts or any other value desired. There are three cables to each circuit and in addition there is a fourth wire which is connected to the tops of the towers (see Fig. 40, Plate III) and which is earthed and normally carries no current. Each of the other wires carries an alternating current at 132,000 volts, but there is a time lag between the current alternations in each wire amounting to one-third of a cycle. The current is said to be "three-phase."

Supply to an ordinary house lighting or heating circuit is tapped off the low tension side of the step-down transformer by connecting the two wires of the house circuit to one of the three wires of the three-phase circuit and to the neutral earth wire. As the earth-wire normally carries no current, it can be a thin wire as compared with the other three wires, so that by using a three-phase alternating current supply cheaper wires can be employed, which is an important consideration when the whole country has to be covered. In addition, a greater output can be obtained

from a three-phase generator than from a single-phase generator.

An account of alternating currents must contain some description of the alternating-current motor. This has been deferred from the chapter on motors on account of the necessity of acquiring first some knowledge of alternating currents. It was seen on p. 42 that every dynamo may be run as a motor if, instead of turning the armature by mechanical means, electric current is supplied to it. This is equally true in the case of the alternating-current dynamo or alternator. It does not follow, however, that such a form of motor is of much use; in fact, the alternating current must resemble the current produced by the machine, not only in having the correct voltage, but it must be in the correct phase at every instant. On examining Fig. 39 it will be seen that, for electrical purposes, each pair of poles with a pair of coils is acting like the direct-current dynamo, and it was shown on p. 42 that if current were supplied to such a machine in the direction in which the machine itself produces current, it would run as a motor, but the direction of running is backwards. But in the alternators there is no commutation and the current must be reversed exactly when the coils have moved forward to the next poles. If the timing is not exact, the current in the rotor poles will get out of step with the appropriate stator poles, and the rotor will no longer be driven. Hence the machine used as a motor must be running at exactly the correct speed, or it will no longer be driven by the current supplied. A motor of this kind is called a SYNCHRONOUS MOTOR, and it will run at only one speed, namely, that speed at which the alternating current supplied is always in the correct phase. This introduces a difficulty in starting, for it must be run up to speed before the supply current is switched on. It cannot, therefore, be started without some mechanical means of driving it, and further, any sudden variation in its load will cause a variation in speed which will probably cause it to get out of step

and then stop. For these reasons the synchronous motor is no use for supplying power, and is only employed in certain smaller pieces of apparatus where constancy in speed is of the greatest importance.

One such application is in the case of an electric clock which is a small synchronous motor geared to drive the clock hands at the appropriate speed when connected to an alternating current supply of suitable frequency. The motor is started by pressing down a rod at the back of the clock which gives an initial kick to the rotor of the motor.

Of late years, there has come into use a type of motor which in being run up to speed is an induction motor (see below). On reaching the proper speed, it is converted into a synchronous motor by the supply of continuous current through the windings of the rotor. If any increase of load should pull the rotor out of phase, it reverts to the induction type and is so brought back into phase.

Many small motors are now driven by alternating current. It will be seen from Fig. 26 that when the currents in the field magnet and armature are both reversed, the direction of rotation of the armature is unchanged. Thus, an alternating current will cause rotation provided that the field magnets are not sufficiently massive to cause an appreciable lag in phase of the alternating current in them.

The INDUCTION motor is not open to the same objections as the synchronous motor, as it can be started by the alternating current which is used to drive it, and in some cases even to start under load. An adequate explanation of the induction motor is not a simple matter. Let us consider a very early experiment by Arago (1825). A magnet A (Fig. 41) is balanced on a needle-point, and in a box underneath it a disc of copper B is caused to rotate. The box protects the magnet from draughts caused by the rotation of the copper disc, but, nevertheless, it is found that the magnet tends to follow the rotation of the disc. If the magnet is a strong one and the disc is massive, it may easily happen that the magnet does actually follow

the disc and rotate after it, but it will never rotate as rapidly as the disc. If, instead, the disc were balanced on a needle-point and the magnet caused to rotate, the disc would then follow the rotation of the magnet. Arago was not able to give the explanation of this effect, but in the light of Faraday's discoveries we can see that when the disc rotates it cuts across the magnetic field of the magnet, and therefore electric currents are developed in it. These currents have a magnetic field, and hence react on the magnet. On general principles it follows that the reaction is always one that endeavours to stop the rotation. It can never assist the rotation, for, if this were the case, once started, the rotation would go on by itself, which is contrary to experience. The reaction between the field of the

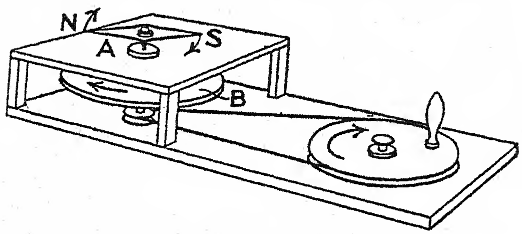


FIG. 41. Arago's rotation.

magnet and the currents produced by rotation will thus tend to reduce the relative motion of the disc and the magnet. But the disc is forcibly driven, and the magnet being pivoted tends, therefore, to follow it. Similarly the disc would follow the magnet if the magnet were driven and the disc pivoted. In general terms we may say that whenever a conductor is situated in a rotating magnetic field, currents are induced in the conductor which by their action with the rotating field make the conductor rotate in the direction of the field, if it is free to turn. We say that a driving couple acts on the conductor. Of course, the lower the electrical resistance, that is, the higher the conductivity of the conductor, the stronger will be the currents developed in it by the rotating magnetic field, and the

greater will be the driving power. For this reason copper is the best material to use for the conductor, with the exception, of course, of silver, which is too expensive for general use.

In order to obtain a motor of any practical use, it is necessary to produce a rotating magnetic field of considerable strength. An alternating current will produce an alternating magnetic field; but this is not a rotating field. It may, however, be considered as the resultant of two rotating fields whose directions of rotation are opposite to each other. Consider the following mechanical model consisting of two wheels A and B (Fig. 42), A being mounted on an axle C and provided with a pin E; B mounted on an axle D and provided with a pin F. The pin E slides in a horizontal slot G, and F in the slot H, the two slots G and H being carried by a rod K which travels vertically. If the wheels A and B rotate with equal speeds in opposite directions, as shown by the arrows, the rod K will be forced to travel up and down at a rate fixed by the speed of rotation of the wheels. Or if the rod be driven up and down with the proper speed it can continue to drive the wheels in opposite directions should they be properly started. In like manner, an alternating magnetic field in one direction, represented by the linear motion of K, may be considered as equivalent to two equal rotating magnetic fields in opposite directions represented by the rotations of the two wheels A and B. Although this equivalence is easy to represent mathematically it is not so easy to represent mechanically, and the rough model will serve to illustrate the general fact that any linear vibration may be considered as equivalent to two equal and opposite

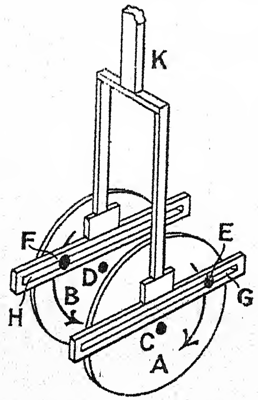


FIG. 42. Model to illustrate the compounding of two opposite rotations to form a single reciprocating motion.

circular movements having the same periodic time as the linear vibration. Thus if a mass of metal is placed in a simple alternating magnetic field, such as would be produced by an alternating current flowing in a coil, it may be considered to be acted upon by two rotating magnetic fields at the same time, but with opposite directions of rotation. Of course under these conditions it will not move; it cannot choose between the two directions in which it is being driven. It is as though two copper discs were being driven in opposite directions, one on either side of the magnet in Arago's experiment. But if the mass of metal be *started in one direction*, by any means, it may be shown by either theory or experiment that the force driving it in the direction in which it is started will increase, while the effect of the oppositely rotating component of the magnetic field gets less. The metal therefore gains speed and will be driven more and more by the rotating magnetic field in its own direction, while the effect of the opposite magnetic field gets less, so that when running at considerable speed it will be driven by the single alternating magnetic field. This is the principle of the single-phase induction motor. The only difficulty yet remaining is to start the rotation in one direction or the other. This is performed by means of a separate circuit which is cut out when once a sufficient speed of rotation has been attained. Such a machine is called an INDUCTION MOTOR. The effect of the rotating circuit is equivalent to rendering the ordinary current equivalent to a polyphase current, the magnetic field of which is an actual rotating field. In polyphase alternating-current working the rotating magnetic field is more simply produced, but polyphase currents are beyond the scope of this book. They present one of the most difficult problems in electrical engineering. It is on account of their complexity that the single-phase induction motor as described above has come into such common use.

There is one interesting modification of the induction coil which acquired great importance in recent years, that

is the MAGNETO, used for causing the spark which fires the explosive mixture of gases in the cylinder of the internal-combustion engine. In the petrol motor the explosive mixture of air and petrol vapour is drawn into the cylinder, compressed by the piston and fired by a spark from an induction coil or magneto. The spark necessary for ignition is now generally produced by a small induction coil, the primary current being produced by a battery of a few storage cells. The popularity of the magneto was due to the fact that it was independent of any charging, and was therefore always ready for use. It was driven by the motor itself and was in all respects automatic. With an efficient magneto, the spark given was sufficient for its purpose even at quite low speeds; but it suffered from the drawback that the motor must be started running, generally by hand, before the magneto would produce any spark, and with the improvement in the design of car batteries and arrangements for charging them while the car is running, the magneto has now largely gone out of use.

With the mechanism of the petrol motor we are not concerned here, but the principle involved in the magneto may readily be grasped. A permanent magnet having soft-iron pole faces N and S (Fig. 43) produces the requisite magnetic field, in which the armature, shown in section, rotates. The core C consists of sheets of soft iron stamped to the required shape and bolted together. P is a primary coil of stout wire and S a secondary coil, consisting of many turns of fine wire, as in the induction coil. In fact, the magneto is really an induction coil; but it differs from the ordinary coil in the manner in which the primary current is produced. Instead of using a battery, the primary current is produced by the rotation of the primary coil in the combined magnetic field of the permanent magnet and the soft-iron core C. It will be seen in Fig. 43 (*a*) that the magnetic lines of force are passing from the pole N, through the core, to the pole S, and that they enter at the end A of the core and leave at B. By the time the

position shown in Fig. 43 (*b*) is reached, the lines of force are entering at B and leaving at A. It is therefore clear that between these two positions they must have been withdrawn from the primary coil and introduced again from the other end, and have therefore cut the primary coil twice. In the act of cutting the primary coil an electromotive force is produced and considerable current will flow. So far the machine resembles a dynamo, and the secondary coil has not yet played any part. But in

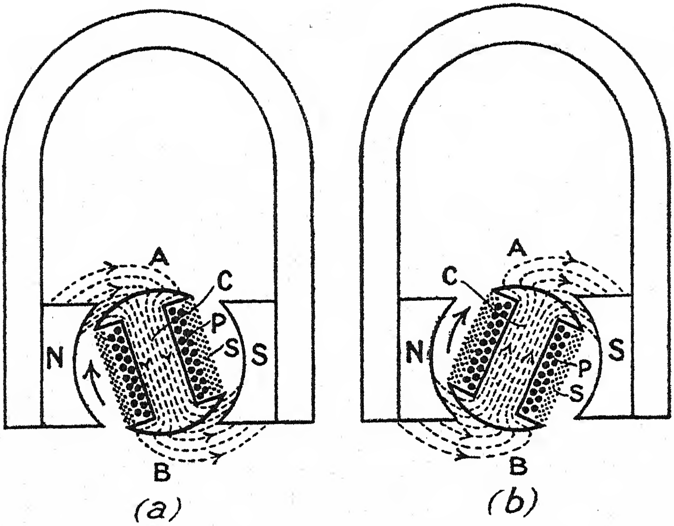


FIG. 43. Circuits of the magneto.

the primary circuit is a key or contact, which is opened just when the current is great and the spark is required. The current in the primary coil is therefore interrupted suddenly, and the two coils then behave like an induction coil, with the production of sufficiently high electromotive force at the sparking plug in the explosive gas mixture to cause the required spark. The intensity of the spark is increased by the action of a condenser, just as in the case of the induction coil, the condenser being usually built into one end of the armature and rotating with it. A wire AB,

Fig. 44, with a thick covering of insulating material, connects the secondary coil of the magneto to the insulated terminal C of the sparking plug, which is screwed into the cylinder cover. The terminal D is connected to "earth," which in this case is the body of the machine, and is represented for electrical purposes by EE,, and supplies the return circuit to the secondary coil of the magneto. Every time the primary circuit of the magneto is broken by the rotating key, the high voltage in the secondary coil pro-

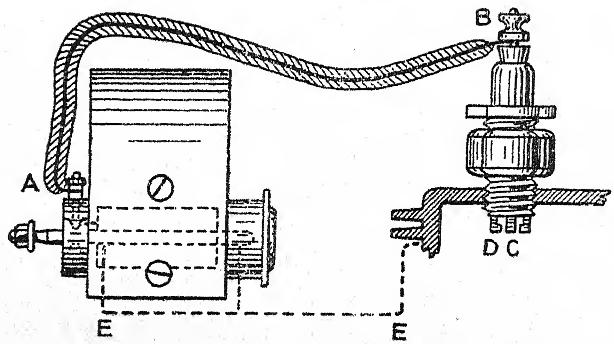


FIG. 44. Arrangement of magneto and sparking plug.

duces a spark between D and C, thus firing the explosive mixture of air and petrol vapour in the cylinder. It would be out of place to describe here the distribution key required when several cylinders are used with a single magneto, or the method of driving the magneto from the main shaft. Such details may be found in works on the petrol motor. The induction coil and its special form, the magneto, rendered possible the great strides which were made in the design and use of the internal combustion engine in the early part of this century.

CHAPTER VI

Electric Lighting

ONE of the earliest known effects of an electric current was the heating effect. By means of a few cells, a fine piece of iron wire may be raised to white heat. The wire will then burn in the air; but if a material such as platinum be used, the wire becomes brightly incandescent, and if the heating be pushed too far, the wire will fuse. It was natural that as soon as electric current could be produced upon an economical scale, its employment for artificial illumination should be attempted. The early attempts, however, were not very successful, and it was many years before electricity could compete successfully with gas for illuminating purposes. The deciding factor is not as a rule the small relative advantage in economy of one form of illumination over the other, but the convenience in use and the character of the light obtained. The fact that electricity does not involve the using up of the oxygen of the atmosphere, with production of objectionable and destructive fumes as does gas, gives it a permanent advantage. The further advantage that the current can be "switched on or off" without the necessity of "lighting" lies of course with electricity.

The earliest attempt to construct an electric incandescent lamp was made by sealing a fine platinum wire into a glass bulb. Edison succeeded in constructing such a lamp. The choice of material naturally fell upon platinum, because of its high melting point and electrical resistance. The commoner metals fuse at a temperature much below that at which light is freely radiated, and platinum has the further advantage that when passing through the fused wall of a glass bulb, the glass will not crack, nor will the

joint loosen as the glass cools, because glass and platinum both contract to the same extent on cooling. The substance employed for the filament must also be highly ductile, so that the filaments may be made sufficiently fine to localise the heating, which occurs in the current circuit, almost entirely to the filament within the lamp. Also the electrical resistance of the material should be high, so that the filament need not be excessively fine or very long in attaining a convenient resistance for the lamp. On constructing a lamp with a platinum filament, it was found at an early stage that the efficiency was increased greatly by pumping out the air from the bulb. The air exerts a considerable cooling effect upon the filament, and exhausting the bulb therefore increases considerably the efficiency of the lamp, so the process has been continued with later types.

Although platinum has a very high melting point, it is necessary to use it at a temperature so near this, for the economical production of light, that any accidental rise in the voltage of the supply is apt to destroy the lamp by melting the filament. Edison, in about 1879, turned his attention to carbon as a material for use in incandescent lamps. The chief difficulty with this material is the production of the filament in the correct shape, for carbon is a brittle material, not in the least ductile. But carbon forms the groundwork of all living matter, and many compounds, such as wood and cotton, are compounds of carbon and hydrogen, with a very small amount of other substances. Also wood is very pliable and can be bent into any shape required, and if heated out of contact with air, the hydrogen and other materials are driven off, leaving hard compact carbon in the shape required. In his early carbon lamps, Edison used bamboo filaments carbonized by heating. But this soon gave place to the process which became employed universally. Cellulose, generally in the form of cotton, is dissolved in a solution of zinc chloride, forming a paste or viscous mass. This paste or syrup is

pressed through a metal die of suitable diameter and emerges into alcohol, where it soon hardens. It is then wound on to a drum and allowed to dry. Owing to its flexibility, the filament is then cut to suitable lengths and bent to its ultimate shape upon round blocks of carbon, many filaments resting side by side on each block. The blocks are then packed in crucibles along with graphite, and heated to about 2000° C., when the volatile substances are driven off and the properly formed filaments remain.

Since the carbon filament must lie entirely within the bulb of the incandescent lamp, it is necessary to attach some wire or lead to it, which passes through the glass wall. As we have seen, platinum is the most suitable material for this purpose, although from its high price, the wire lead usually consists of platinum only where it actually passes through the glass. The joint on to the carbon is made by laying the wire and carbon in contact in a material such as benzole, which is rich in carbon, and passing an electric current through them. The heating at the joint is then sufficient to decompose the benzole, and a hard compact mass of carbon is deposited on the joint, making a most efficient seal.

Before placing in the bulb, a process called "flashing" is performed. This consists in raising the filament to incandescence by means of a current, while situated in some hydrocarbon vapour such as benzole. At the temperature of incandescence of the filament, the hydrocarbon vapour is decomposed, carbon being deposited upon the filament. This process has three distinct advantages. The surface of the filament is rendered smooth and suitable for uniform radiation of light, and the deposition can be continued until the thickness of the filament is increased to a suitable amount for the purpose for which the lamp is to be used. Further, the filament at its thinner parts becomes hotter than at the thicker parts, with the result that the carbon is more freely deposited on the thinner parts. This process of flashing therefore renders the filament

uniform throughout its length and removes the "patchy" appearance which a carbon filament possesses that has not been subjected to flashing.

After the filament is "flashed" it is sealed by the glass-blower into the bulb, and fixed into its metal cap; the air is exhausted, leaving a fairly good vacuum, and the lamp is then sealed off at the point of connection to the air-pump (Fig 45). The carbon filament lamp must, of course, be highly exhausted, not only on account of the cooling effect of any air remaining, but because the oxygen of the air would combine with the carbon at the temperature of incandescence, so that the filament would be burnt up instantly.

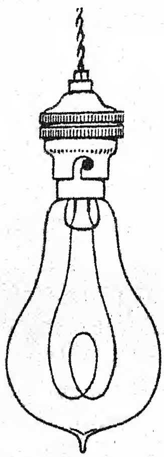


FIG. 45. Carbon-filament lamp.

The problem of illumination involves the question of the rate of emission of light from hot bodies. At low temperatures the emission does not affect the eye although it produces warmth; it is called radiant heat. If the temperature of a body be raised to about 700° C. the radiation emitted consists of rays which we call red, which produce an effect upon the eye, and we say that the body is at a "dull red heat." At a higher temperature the body becomes "white hot," and in order to give out light of the same character as daylight, that is, light from the sun, the temperature of the body would require to be about 6000° C. The higher the temperature that can be attained for the radiating body, the greater will be the proportion of the energy supplied to it which is radiated as light, and the nearer will the character of the light emitted approach to that of daylight. Thus the efficiency will improve with rise of temperature of the filament of the incandescent lamp. A word of warning is necessary here. The radiation referred to here is a pure temperature effect corresponding to what in physics is called a "black" body, to which carbon

approximates. It must not be confused with the "selective" radiation which many substances in the gaseous form emit, as for example, the yellow light of incandescent sodium vapour or calcium vapour, the crimson of strontium, or the green of thallium. The employment of such substances to obtain flames of various colours in the arc lamp will be found on p. 90.

The carbon-filament lamp has not a very high efficiency, as it requires about 2·5 to 3·5 watts for every candle-power. The reason is that, on raising the temperature of the lamp above the value for ordinary running, the carbon becomes disintegrated and is deposited as a black film on the inner surface of the glass bulb, and the filament soon breaks. Hence for many years a search was made for some substance of which the filament could be made, which would not melt or disintegrate at a temperature much higher than is allowable for the carbon filament, so that the fraction of the energy supplied to the lamp which is radiated in the form of light should be greater, and of a colour more nearly approaching daylight. Attention was naturally turned towards the rare metals, some of which have exceedingly high melting points.

In order to obtain some idea of the type of material required, it may be noted that on the centigrade scale of temperature, water freezes at 0° and boils at 100°. Lead melts at 327° C., gold at about 1060° C., platinum at 1760° C., osmium 2200° C., tantalum 2900° C., and tungsten 3000° C. approximately, while the temperature of the sun is somewhere near 6000° C. The temperature of the carbon filament of an incandescent lamp is probably in the neighbourhood of 1300° C. The three metals osmium, tantalum, and tungsten have all been employed for the construction of the filaments of incandescent lamps.

The difficulty encountered in the early attempts to construct a metal-filament lamp is that of obtaining a sufficiently thin filament to keep the current from being excessive when the lamp is used on ordinary voltages.

Tantalum is ductile and can be drawn into fine wires; but in the early lamps a considerable length of wire had to be used, the wire being looped backwards and forwards upon a supporting framework. Tungsten is an exceedingly useful metal for the construction of filaments, but unlike tantalum it is brittle, and could not be drawn into the form of wire. Successful attempts were made by mixing powdered tungsten with a gummy material and forcing the paste through a fine hole of the required diameter. The filament so formed was wound on its supports and the gummy material driven off on heating the filament by passing an electric current through it. The filament then consisted of fairly pure metal, but required great care in handling owing to its brittleness. The Osram lamps, which played such an important part in displacing carbon lamps from ordinary use in the year 1908, were of this form.

Undoubtedly the greatest achievement in electric incandescent lighting is the production of the drawn filament of tungsten. Tungsten is soft and easily welded at high temperatures, and on being welded into one mass by hammering, is capable of being drawn into wire of suitable diameter for lamp filaments. Such lamps have very good efficiency (about 1 watt per candle-power), and are durable. They should run for 1000 hours without the blackening of the bulb being excessive. Over-running of the lamp, that is, running it at too high a temperature, improves the efficiency but spoils the lamp, owing to the blackening, as in the case of the carbon-filament lamp.

This difficulty was partially overcome by filling the bulb of the lamp with the gas nitrogen or now more commonly neon, at about half the atmospheric pressure. Nitrogen or neon being inert does not injure the filament and the gas in contact with the hot filament expands and rises. This upward current of gas carries with it the disintegrated part of the filament which is deposited in the upper part of the bulb and so does not obstruct the light emitted. In this way, an efficiency of about half a watt per candle-power is

obtained. The presence of the gas helps to prevent the disintegration of the filament but the upward movement of the gas which is caused by the hot wire serves to cool the latter, and this tends to offset the higher efficiency which results from the increased current which can be employed. The cooling effect is greatly reduced if the wire of the filament is wound into a very fine spiral so that the amount of gas in the vicinity of a given length of wire is much less. By this means the efficiency is improved and these gas-filled lamps have now almost entirely superseded metal filament lamps.

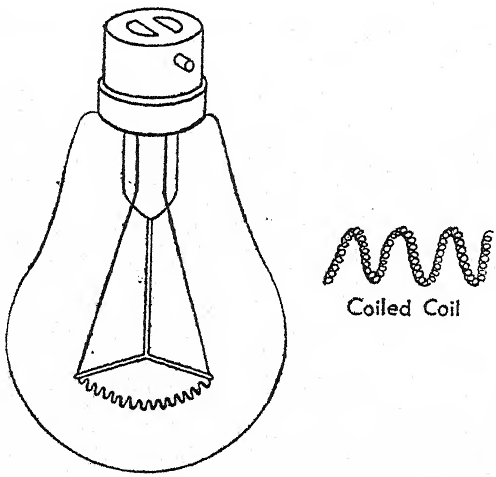


FIG. 46. Gas-filled lamp.

Fig. 46 illustrates such a lamp, a length of the coiled coil filament magnified many times being shown at the right-hand side of the figure.

It has been known from early times that when an electric circuit is broken, a spark occurs at the point of break. This spark is evidence of very high temperature, for the quality of the light emitted shows it to be due to the metal of the conductor in a state of vapour. In most cases the spark is soon quenched, but if the electromotive force driving the current is fairly great, the metallic vapour

and the gas at high temperature form a conducting bridge and the current persists. In this case the phenomenon is called the ELECTRIC ARC. The first description of an undoubted electric arc, as distinguished from a spark, is due to Sir Humphry Davy in 1812, who, using a battery of 200 large cells, obtained between carbon rods a continuous "arch of light," from which the name "arc" has arisen. When the electric arc occurs between metals they are melted, the gap lengthens rapidly, and the arc is quenched. With carbon, however, there is no melting, and the arc may persist for a long time. With an electromotive force of over 40 volts or thereabout in the circuit, the electric arc between two carbon rods is easily produced. It is thus seen that the useful production of an electric arc depends upon the peculiar properties of the substance carbon. Carbon exists in nature in many forms. It occurs in the transparent crystalline form, and is then called diamond, also in the form of a compact mass, when it is called plumbago or blacklead, and it is also an essential constituent of all living materials. It is the chief constituent of coal, and if the gaseous portion is driven off by heat, an impure mass of carbon remains, which is called coke. One of the most peculiar properties of carbon is that of becoming volatilised when heated to a very high temperature, without first going through the liquid stage. Most solid substances melt when the temperature is raised sufficiently, and at still higher temperatures volatilise or pass into the form of gas or vapour. But under no conditions that we can produce will carbon liquefy. Consequently, if the electric arc be formed between two rods of carbon, the rods may volatilise and burn away at the high temperature of the arc, but they will not liquefy. For this reason carbon is always used when it is required to produce an electric arc.

The form of the arc is important, and it may be studied by examining the arc formed between two carbon rods of about one centimetre diameter. Owing to the brightness of the hot carbon rods it is not safe to look at the arc with

the naked eye; blackened glass must be used between the arc and the eye. Or an image of the arc may be produced on a white screen by means of a lens, such as a reading glass, which method has several advantages. The image is not too bright to be looked at directly; it may be larger than the arc itself, and measurements of the length of the arc may be made upon the screen, which could only with difficulty be made upon the arc itself. The arrangement may be seen in Fig. 47, in which the actual arc is seen at D. In order to start the arc it is necessary that the carbons should be first brought into contact and then separated. Where the carbons touch, the electrical resistance is con-

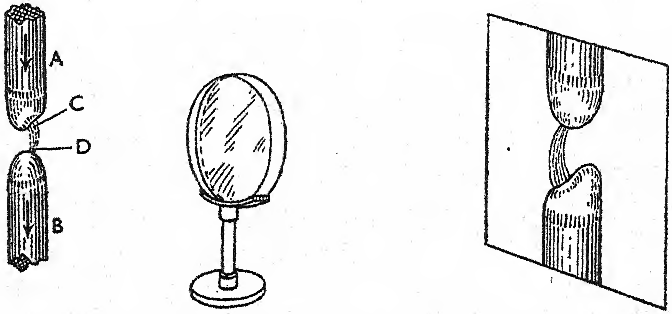


FIG. 47. Method of examining an electric arc.

siderable, and the heat caused by the current in flowing across this place of high resistance is so great that some of the carbon burns and some volatilises, the hot gases produced forming a conducting bridge, across which the current flows from carbon to carbon as the two are separated. This process is called "striking the arc." The rudimentary explanation of it given here is imperfect in many ways. For example, it is known that hot bodies emit charges of negative electricity called electrons (see Chapter XI), and that these play a large part in carrying the current across the gap. But we must be content here with a description of the phenomenon without too strict inquiry into its mechanism.

On examining the arc it will be seen that it forms a pale blue band of gas D (Fig. 47) of curved form, from one carbon to the other. From this curved form the name "arc" is derived. The luminosity of the arc itself is only small, but the ends of the carbon rods, between which the arc is formed, are very hot, and give out a considerable amount of light. One spot is the brightest of all, and from it most of the light is emitted. This spot is situated upon the carbon by which the current enters, which is called the POSITIVE CARBON. Owing to the high temperature of this spot, from which the arc springs, the carbon wears away more rapidly here than elsewhere, so that a cup or CRATER is formed. Whatever may be the shape of the end of the carbon before the arc is struck, it soon wears down to a slightly conical form, ending in the crater C (Fig. 47). The negative carbon B does not present any crater, and soon acquires a nearly conical form, owing to the burning of the carbon rod at its edges. The crater is the source of most of the light given out by the electric arc, only a comparatively small amount being given out by the actual arc and by the negative carbon. This limitation of the brightly luminous area has one disadvantage, which is, that the other parts of the carbons, particularly the negative carbon, are apt to obstruct the light from it. For this reason, when the light is required for projection purposes, or in the case of a searchlight, the carbons are tilted, as in Fig. 48, to allow a free passage for the light in the direction required. There is also one great advantage in the luminosity being confined to the crater, for it gives what is very nearly a point source of light. This is of considerable importance in

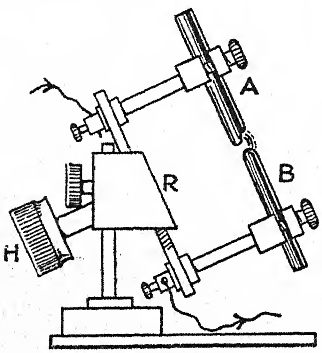


FIG. 48. Hand-feed arc lamp for projection lantern.

the case of a projection lantern, as it is only by using a small source of light that a brilliant, uniformly illuminated image can be produced. In practice it is found that the bright spot wanders about the carbon, giving rise to disturbing fluctuations in the light emitted in any given direction. In order to obviate this difficulty the positive carbon is made with a core of carbon softer than the remainder. The softer carbon volatilises easily, and the arc then springs only from the edge of the core, so that its wandering is limited in extent. The positive carbon, owing to the fact that it is cored and also on account of the high temperature of the crater, burns away more rapidly than the negative carbon, and is for this reason usually made of larger diameter.

The amount of light given out by the arc depends upon the size of the bright spot or crater, and this in turn depends upon the current. With an increase in current the crater does not become hotter, but increases in size. It has been estimated by Violle that with carbon the temperature of the crater is about 3500° C.

It must be remembered that the light emitted by the crater may not all be usefully employed, as much of it may be obstructed by the negative carbon.

It was suggested by Sir William Abney that the temperature of the crater is the volatilisation temperature of carbon. This would explain the constancy of the luminosity per unit area of the crater. Many workers have helped to elucidate the phenomena exhibited by the electric arc, but the name of Mrs. Ayrton deserves particular mention. To her is due the explanation of the hissing of the arc when the current is too great and the arc too short. The crater is then too large to occupy the end only of the carbon and extends up the side. The air can then reach the crater and the carbon burns, instead of merely volatilising, and in this case the well-known hissing sound is produced. The connection between area of crater, current and candle-power is important. Forrest found that

each square millimetre of the crater emits an amount of light corresponding to 172 to 174 candle-power, and it has been shown by N. A. Allen that the current is directly proportional to the area of crater, being 0·746 ampere per square millimetre. This gives a candle-power of 232 per ampere.

With an alternating current supply, the direction of the current is reversed so rapidly that no crater is formed; the two carbons form nearly flat surfaces opposite to each other, and the efficiency of the arc as a light producer is lessened by the obstruction of the light by the carbons themselves.

From the moment of the discovery of the electric arc, it was obvious that the great brilliance of the crater would provide a convenient means of producing light by means of the electric current. However, it was not until 1876 that the first serious attempt was made to use the arc for lighting, the reason being that the economical production of electric current took many years to develop. In that year Jablochkoff employed two parallel carbon rods, separated by an insulating material. The arc between the tips of the rods being started, the carbons gradually burn away, the insulating material being dissipated at the same time. These were called Jablochkoff's candles. They soon gave place to more convenient arc lamps.

Arc lamps may be run from electric mains at any voltage, provided that the 40 volts required for the arc itself is exceeded. With mains at a higher voltage, some resistance must be placed in series with the arc; in fact, some such resistance must always be used because the arc by itself is unstable: the current tends to increase rapidly or decrease rapidly, since the resistance of the arc gets less with increasing current and gets greater with decreasing current, thus necessitating the use of a steadying resistance in series with the arc.

For use with a projection lantern, the simple hand-feeding arrangement shown in Fig. 48 is highly efficient. By means of the handle H and the racks and pinion R

the carbons A and B may be approached to each other until they touch. The operator then separates them, thus striking the arc. The length of the arc for proper running can then be adjusted from time to time. But for running in inaccessible places and for public lighting it is necessary to provide some automatic feeding mechanism for the carbons. As the carbons burn away, the arc gets too long, and the current drops. On the other hand, if the arc is too short, as on striking, the current is too great. This variation in current is usually employed to make the necessary adjustment in the position of the carbons for proper running. Many forms of mechanism have been devised for regulating the length of the arc automatically, but most of them depend upon the fact that an iron cylinder, situated partly inside a solenoid, or long coil, carrying an electric current, is pulled into the solenoid with a force which depends upon the strength of the current. The principle of this method is illustrated in Fig. 49. The current, entering by the terminal A, passes through the solenoid B consisting of thick wire, since it carries the whole current of the arc, which may be 20 to 30 amperes. The iron plunger C fits loosely into the solenoid, and at its base carries the holder D of the positive carbon. The current passes from the solenoid through the arc, and out by way of the negative carbon carrier E and the terminal F. Before the current passes, the weight of the iron plunger and the positive carbon ensures that the carbons shall be in contact. On switching on the current, the pull of the solenoid on the iron plunger raises the positive carbon from contact with the negative carbon, and thus the arc is struck.

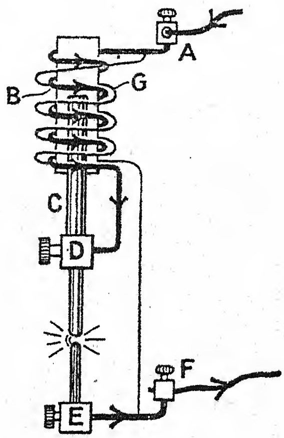


FIG. 49. Principle of the automatic-feed arc lamp.

As the carbons separate, either on striking the arc, or on the burning away of the carbons, the electrical resistance of the arc increases so that the current drops. This, of course, decreases the pull of the solenoid on the iron plunger, which allows the positive carbon to drop slightly, so shortening the arc. For a given arrangement of solenoid and plunger the arc will only be steady for a given current, and its length is automatically adjusted until this length is attained. An additional coil G is seen in Fig. 49, which is made of a considerable length of fine wire, placed in parallel with the arc. When the resistance of the arc increases, the current in G increases also, and when the resistance of the arc falls, the current in G decreases. Since it is wound in the opposite direction to the main coil B, and is oppositely affected by the arc, the result is that it helps the main coil in maintaining the adjustment of the length of arc.

Such a simple arrangement as that just described would not be found very suitable in practice, as the motion of the carbons would be jerky and the regulation would not be sufficiently delicate. The principle, however, is applied in the form of the automatic arc lamp of which there are many patterns. It is usual to balance, to some extent, the weight of the moving carbon with its holder, and provide some form of ratchet and pawl for moving the arc forward by small steps as the carbons burn away.

Considerable advantage is gained by enclosing the arc in a glass bulb or globe which is made very nearly airtight. When the arc is running, the air, or rather the oxygen of the air, in the globe is soon used up in forming carbon dioxide (CO_2), the product of combustion of the carbon in air. When the oxygen in the globe is all used up, no further combustion of the carbon can take place. Also a much greater length of arc may be used with this ENCLOSED ARC than with the open type, and a higher efficiency is attained. A common value for the illuminating power of an open arc is about 1000 candle-power, and for an enclosed arc 2000 candle-power, with an efficiency of 1·5

to 2·0 candle-power per watt for the former, and 3 to 4 candle-power per watt for the latter.

In the older type of arc lamp the useful illumination is derived almost entirely from the crater, and this, as we have seen, is liable to be hidden by the negative carbon. The increase in length of the arc obtained in the enclosed type leads to a greater efficiency, because of the smaller obstruction due to the negative carbon; but a further increase in efficiency was obtained by Carbone by using a very long arc and placing the carbons so that there is no obstruction of light by the negative carbon. The two carbons are inclined at a small angle to each other, and the arc takes place at their lower ends, as will be seen in Fig. 50. It is well known that an arc produced at the lower end of a pair of carbons will tend to be carried up them by the hot-gas currents produced. This effect would be deleterious in the present case, and the device of using a magnetic field to spread out the arc in a downwards direction is employed. The current flowing through the arc also flows through two coils A and B, and so magnetises the iron ring whose poles are at N and S. The magnetic field due to this ring is at right angles to the direction of the arc itself, and therefore will exert a force upon the arc, as was seen on p. 41, urging it downwards. Another device consists of a white porcelain reflector P, called the ECONOMISER, which not only reflects the light downwards but serves to protect the mechanism of the lamp from the hot gases arising from the arc. It has also the effect of enclosing the arc partially, for the burnt gases are caught by it, and so by protecting the arc from the air, increases

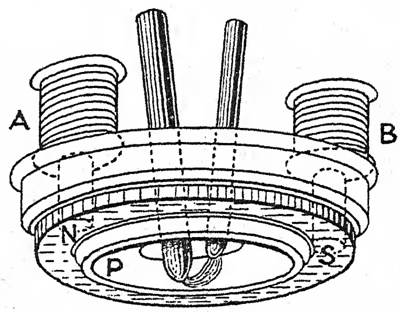


FIG. 50. Carbone and flame arc lamp.

the life of the carbons and assists in their burning away at equal rates.

The "Carbone" lamp prepared the way for the more modern FLAME ARC, which possesses all the characteristics of the "Carbone" lamp, even to the horizontal magnetic field and the porcelain economiser, but presents the new feature of rendering the arc itself brightly luminous, so that the light emitted is no longer entirely due to the positive crater. The flame arc proper may be said to date from the times of the work of Bremer on the addition of certain fluorides to the carbons, to give the arc a high luminosity due to the emission of light by certain materials at very high temperature. Thus many metallic vapours when raised to a very high temperature emit light of a particular colour; the golden yellow of the sodium flame is very well known, as well as the crimson flame of strontium. In the construction of flame arc carbons, strontium fluoride is used for the red arc, cerium fluoride for a white arc, but for the most common of all, the yellow flame arc, calcium fluoride is used. The fluoride is powdered and mixed with finely ground carbon and made into a paste with a solution of potassium silicate. This paste is pressed into a circular hole running the whole length of the carbon, which is made in the ordinary way; that is, finely ground gas retort carbon is mixed with soot and tar and pressed through dies and baked at high temperature.

The core containing the fluoride may have various sizes and compositions dictated by experience, but it is not found that any great advantage accrues from having both carbons impregnated. It is sufficient if the positive carbon alone possess a core containing the fluoride, the core of the negative being the soft core such as is used with the ordinary arc.

One other feature of the flame arc should be noticed. Owing to the desirability of having long and thin carbons, their electrical resistance is considerable, and would vary very much as the carbons burn away. Hence a second

hole is made in the carbon, down which a brass wire passes, the wire being bent over at the upper end, serving to make good electrical contact with the holder. This wire carries most of the current, and reduces the electrical resistance; it volatilises or burns away at the temperature of the arc.

Yellow flame arcs present a very efficient form of electric lighting. Although their colour renders them objectionable for indoors, yet in open spaces their characteristic colour has a cheery effect, and their economy is easily seen from the fact that the various makes of lamps have efficiencies varying from 3 to 10 candle-power per watt.

An important use of the electric arc is for welding. Metal plates such as those forming the sides of a ship may be welded together by moving an arc along the line of the junction of the plates. The heat of the arc is so great that it melts the metal of the plates and unites them firmly together. The arc is also used in the electric furnace.

Arc lamp lighting is not now very widely used, fluorescent gas-filled tubes having taken its place. This type of lighting will be referred to again in Chapter XI.

Safety devices are necessary in all electric circuits. These take the form of circuit breakers of various types, the simplest form being the fuses installed in lighting circuits. Such a fuse consists of a wire usually made of a tin-lead alloy which melts at a fairly low temperature: if an excessive current flows through the circuit the heating effect of the current melts the wire and automatically breaks the circuit. In a house lighting circuit, there are usually several fuses which operate at different current strengths: the main house fuse melts only if a large current flows and is inserted to prevent damage to the electricity company's mains.

CHAPTER VII

The Electric Telegraph

FROM the very early years of the nineteenth century many people were attracted by the idea of using electricity for the conveyance of messages. The earliest attempt consisted in discharging a Leyden jar into an insulated wire at the sending station, which caused the divergence of a pair of suspended pith balls at the receiving station. Considerable ingenuity was expended upon devising a system of signals, but such methods break down on account of the very high insulation required for the wire or line and the signalling apparatus. The leak of electricity from the line is so great that the system is useless over any but the smallest distances. Electric telegraphy only became practicable after the discovery of Oersted that an electric current is accompanied by a magnetic field, and the later discovery that the magnetic field could be intensified by winding the wire carrying the current into the form of a coil. The use of the electric telegraph gave a great impetus to the study of the electric current, and was for many years the only branch of electrical work which had any commercial application. Much of the work of Wheatstone and of Kelvin, which was afterwards found to be applicable to other branches of electricity, arose through their study of the problems connected with telegraphy. In 1839 Cooke and Wheatstone devised a system by which the letters of the alphabet could be telegraphed from one place to another, and the printing telegraph of Hughes came at a later date. On account of its rapidity in working and simplicity of apparatus, the simple circuit using a key and battery at one end of the line and some form of galvanometer or indicator at the other end came into

general use. A current of short duration, corresponding to a DOT, and one of longer period corresponding to a DASH, can, by combining them into suitable arrangements, be made to indicate every letter of the alphabet, together with the numerals and certain special signs for stops and official instructions. The system now generally employed is the Morse code, which is here given.

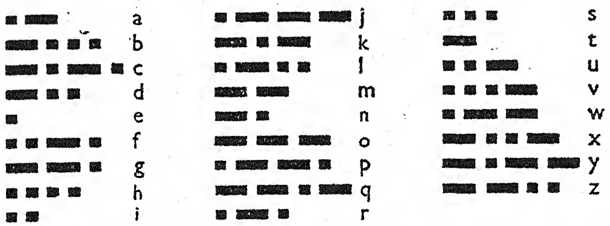


FIG. 51. Morse code.

The simplest form of apparatus necessary for using the Morse code of signalling is merely a key K (Fig. 52) and battery B at one station, and some form of galvanometer or indicator G at the other, the two stations being connected by a pair of insulating conducting lines L_1, L_2. One of these lines may be dispensed with if the conductors are

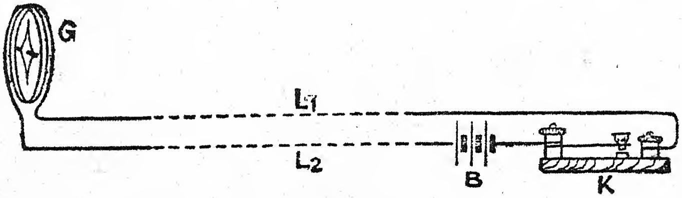


FIG. 52. Simple electric telegraph.

properly EARTHED at each station, so that the current which flows from one station to the other through a line or cable returns through the ground or, in the case of a submarine cable, through the sea. The proper earthing of the line is important; it is not sufficient to put the line in contact with the ground, but it must be connected to plates buried several feet deep in moist earth. On depressing the key

K for a short or a long time the needle of the galvanometer is deflected for a corresponding interval, and the dots and dashes of the Morse code may be so conveyed. The simple arrangement of apparatus shown in Fig. 52 would, of course, only enable signals to be sent in one direction. In practice the apparatus must be duplicated for transmission in both directions.

There is not a great variety in the type of key or of battery used for ordinary telegraphy; but there are several distinct forms of receiving instrument. In Fig. 53 is illustrated an ordinary Morse key. It will be seen that on depressing the knob at the end of the brass arm A, the

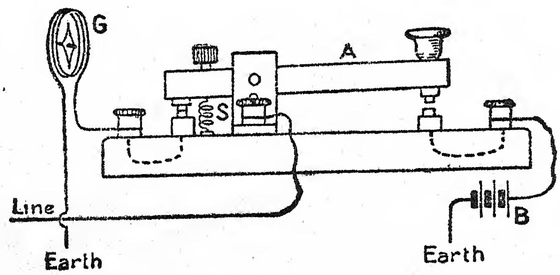


FIG. 53. Morse key used for sending.

battery B is connected through the key to the line, and a current is caused to flow in the receiving instrument at the distant station. On releasing the key, the spring S raises A and disconnects the battery from the line. It also causes contact at the back stop, which brings the receiving instrument into circuit for the reception of signals, so that only one line to connect the two stations is necessary.

Of the receiving instruments, the form most commonly used in the post office telegraphic service is the sounder, one pattern of which is illustrated in Fig. 54. The current from the line passes through the two coils A and B of an electro-magnet which attracts the piece of soft iron CD, and so pulls down the brass arm EF of the lever, causing the stop G to strike the metal pillar, thus producing a sound

or click. When the currrent ceases, a spring causes the lever to spring back, and in so doing another click is caused when it strikes the stop H. The interval between the clicks marks the duration of the current, and therefore corresponds to a dot or a dash of the Morse code. In the case of the Morse inker a strip of paper is caused to travel by clockwork and passes under the lever, which in this cases carries an inked wheel, so that the dots and dashes are marked upon the paper as it travels. This method has the advantage over reading by sound, that the message can be checked by the operator without the necessity of resending it. If the currents in the line are feeble, an arrangement

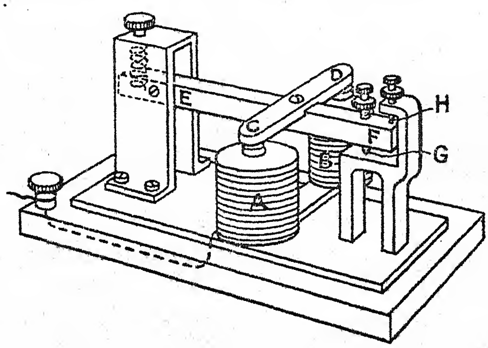


FIG. 54. Sounder for receiving.

similar in principle to the sounder, and called a RELAY may be used, the function of which is to close a local circuit containing a battery and sounder or printing machine. The local battery may then be made sufficiently strong to work the mechanism of the printer.

For railway telegraphic work it is more usual to employ a detector having a permanent magnet, so that currents in opposite directions will cause opposite deflections. A current in one direction will then deflect the north pole of the magnet to the left (Fig. 55) and the pointer P attached to the magnet will strike the left-hand stop A, which indicates a dot. Or, if the current is in the reverse direction, a deflection in the opposite direction is caused and the

pointer strikes the stop B, indicating a dash. If two bells having different sounds are used for A and B the dots and dashes may be recognised by the operator by ear, and the necessity of watching the instrument is avoided.

When extremely feeble currents only are to be detected, as in transmission over long submarine cables, a much more sensitive indicator than either of the two last described must be used. Lord Kelvin, then Prof. W. Thomson, devised such an instrument especially for use with the trans-Atlantic cable. It is really a very delicate galvanometer, with a special form of inker, which he called a SIPHON RECORDER. Special interest attaches to the siphon recorder, as it is the first case in which the galvanometer consisted of a coil suspended in a permanent magnetic field. It gave rise to a type of galvanometer which is now used almost universally, and is known as the suspended coil galvanometer, to distinguish it from the older form in which the coil that carries the current is fixed, a very light magnet being suspended at its centre.

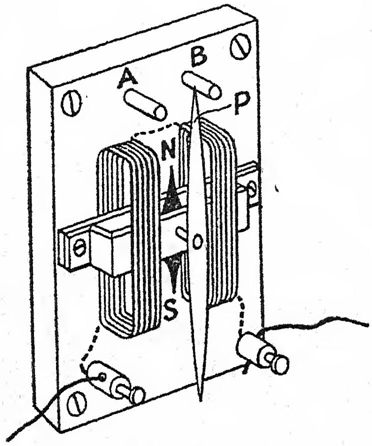


FIG. 55. Railway telegraphic receiver.

Since in the siphon recorder the magnet is fixed, very powerful magnetic fields can be employed, but, of course, the coil, being suspended, must now be made very light, o that the suspension may not hinder its motion. This, however, is no disadvantage when only feeble currents are to be observed. The current from the line L (Fig. 56) passes by means of flexible wires to the suspended coil ABCD of many turns which hangs in the field of a powerful magnet NS. If the current flows down AD and up CB it follows from the rule on p. 41 that AD is driven

outwards from the support and BC inwards. Since A and B are attached by fine silk threads to the rocker EF, this is tilted by the motion of the coil. The rocker EF carries the actual tube or siphon GHK, the end G dipping into a vessel of ink and the end K resting against a strip of paper which is driven forwards by clockwork. When there is no current flowing through the coil, K is at rest, and leaves a straight line track of ink upon the moving paper. But a current in one direction in the coil causes a deviation of the ink line to one side, and a current in the opposite direction causes a deviation to the other side. One side

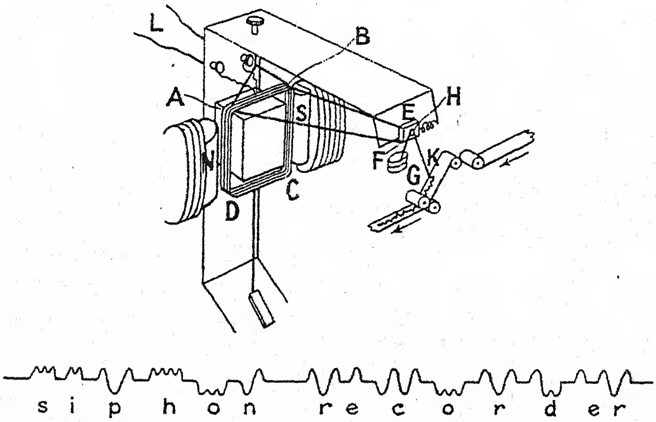


FIG. 56. Kelvin siphon recorder.

corresponds to a dot and the other to a dash, so that the Morse code may be used. The appearance of a record is shown in the lower part of Fig. 56.

As the electric telegraph became more familiar to the public the demand for its use increased until the telegraph lines laid were unable to transmit all the messages required. The ingenuity of telegraphic workers was therefore directed to the problem of increasing the utility of each line. This has been attained in two ways, first, by devising arrangements by means of which two or more messages may be transmitted over a line at one and the same time, and

second, by increasing the actual rate of transmission of the message far beyond that which can be acquired by a human operator. Under the first heading there are many systems, known respectively as duplex, quadruplex, or multiplex systems, according to whether two, four, or more messages can be sent simultaneously over one line. Of the duplex type there are two common systems, one known as the DIFFERENTIAL SYSTEM, which is generally used on land lines, and the other the WHEATSTONE'S BRIDGE SYSTEM, which is used in connection with submarine cables. The differential duplex system is illustrated in Fig. 57, in which the two

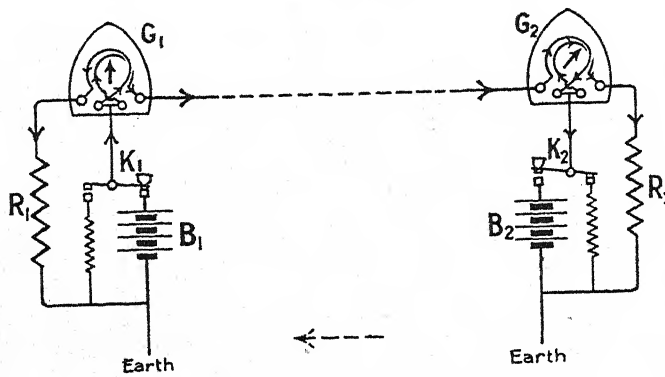


FIG. 57. Differential duplex telegraph.

instruments G_1 and G_2 are of the galvanometer type shown in Fig. 55. But in this case the coil of each galvanometer is wound in two parts, the two parts being exactly alike. If, then, the current flows the same way through the two halves of the coil, the effects will be added, and the needle will be deflected by the magnetic effects of the two halves. If, on the other hand, the current flows in opposite directions round the two halves, their effects on the needle are in opposition and will cancel each other, so that the current will not affect the needle. In Fig. 57 it will be seen that the Morse key K_1 is depressed so that the battery B_1 sends a current through the two coils of G_1 in opposite directions, and therefore this current does not disturb the needle of

G_1. But the current to the line passes round both coils of G_2 in the same direction, with the result that the needle of G_2 is deflected. Hence the depressing of K_1 affects the galvanometer G_2, but not G_1; and similarly the depressing of K_2 affects the galvanometer G_1 only. It follows that messages can be sent in both directions along the line at the same time without causing any confusion. In place of the galvanometers shown, sounders or relays may be used, without altering the principle of the working, but they must, of course, be constructed with coils differentially wound. The resistances shown at R_1 and R_2 are balancing resistances to ensure the equality of the current in the two coils of the instrument at the sending station. If the currents in the coils were not equal, their effects would not cancel, although their directions might be opposite.

The WHEATSTONE'S BRIDGE duplex system depends upon a principle well known in electrical testing under the name of the Wheatstone's bridge. In the arrangement shown in Fig. 58, the currrent from the battery B_1 enters the system of resistances at A, and then divides, one part going through R_1, L and the distant station to earth, and the other going through R_2 and R_4 to earth. Now in such a system, if we let R_3 represent the combined resistance of the line and the distant station, the principle of the Wheatstone's bridge states that no current will flow through the galvanometer G_1 when the four resistances R_1, R_2, R_3, and R_4 form a simple proportion; that is, when $\frac{R_1}{R_2}=\frac{R_3}{R_4}$. It follows, then, that if R_1 and R_2 are equal, and R_4 is adjusted to be equal to R_3, this proportion is fulfilled, and although the current is flowing to the distant station, none flows through the galvanometer G_1. At the distant station the current arriving at B will divide, part going through the galvanometer G_2, so that this galvanometer always indicates a current when the key K_1 is depressed. Similarly, on proper adjustment of the resistances being made, the depression of the key K_2 will affect the galvanometer G_1,

but will not affect G_2. It is therefore seen that the messages going in opposite directions are independent of each other, and duplex working has been attained.

A further extension of usefulness of the line is obtained by using two kinds of key and two kinds of relay at each station. One key merely reverses the current in the line, and these reversals only affect one of the relays, since the other relay is not sensitive to reversal of small currents. The other key switches in more cells, and therefore increases the current in the line, and so affects the second relay only, which is only sensitive to change in strength of the current. Thus two messages may be sent along one

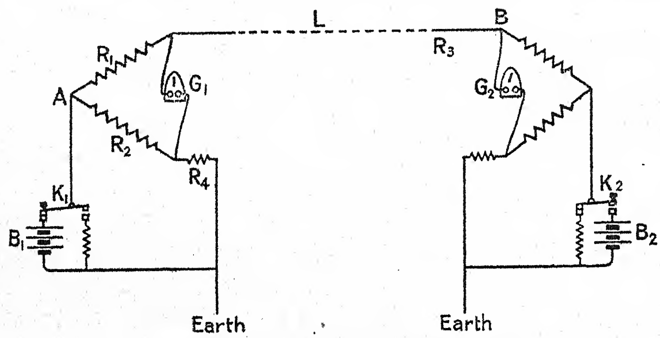


FIG. 58. Wheatstone's bridge duplex telegraph.

line in the same direction at the same time without interfering with each other. This is called DIPLEX WORKING. Since each of the arrangements may be applied along with a duplex arrangement, either differential or bridge, it follows that the line may be used to transmit four messages at the same time, two in either direction. Such an arrangement is said to be QUADRUPLEX.

Still further advantage may be taken of a single telegraph line by employing a MULTIPLEX SYSTEM. This necessitates the use of two motors which are driven at exactly the same speed, one being situated at each station. Each motor drives an arm which travels over a disc divided into conducting sectors, insulated from each other. A trans-

mitting instrument at the sending station is connected to the sector which is joined to the line at the same instant as the corresponding receiving instrument at the distant station is joined to the line through its sector.

Thus, if the two conducting arms A and B are driven at the same speed, the instruments connected to each sector, say No. 2, as shown in Fig. 59, will be connected together once in each revolution of the arms. Four other sets of instruments may be connected to other sectors, so that five sets are in use simultaneously. The currents between each set of instruments will, of course, be intermittent, since each set is using the line for less than one-sixth of the time of

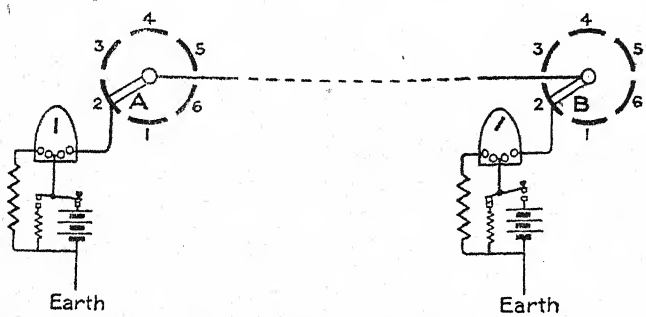


FIG. 59. Multiplex telegraphic system.

revolution of the conducting arm. But if the number of contacts per second is great enough, and the receiving instruments are somewhat sluggish in their movement, the intermittence of the current is not noticed. This may be effected either by driving the arms at considerable speed or by dividing the disc into more than six sectors, say 24 or 36, so that each circuit uses the line four or six times per revolution. Both methods are employed in practice. The arms may be driven by clockwork or by electric motors, but in either case they must be regulated to run at exactly the same speed. This synchronising is effected by using one of the sectors at each station for sending a current which accelerates or retards an electric controlling device, according as it arrives just after or just before the time

corresponding to exact running. Thus, if the rotating arm at either station lags slightly, the impulse causes it to be accelerated, and if it should be running slightly too fast the impulse retards it. It is clear that the utmost importance attaches to the running of the arms at the same speed at the two stations, and any minute variation in speed must be corrected immediately.

It has already been mentioned (p. 98) that there is a second method of increasing the usefulness of a telegraph line, namely, by devising a mechanical method of sending the intermittent or reversed currents corresponding to the dots and dashes of the code of letters. The speed of signalling by hand is not usually greater than about thirty words per minute, so that the time required for transmitting a message consisting of several thousand words in this

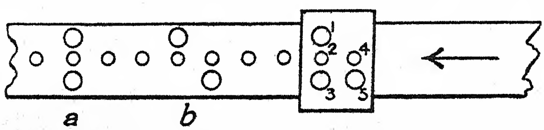


FIG. 60. Ribbon of Wheatstone automatic telegraph.

way would be considerable. It is therefore usual to divide the message into sections, and several operators are working at the same time, each operator being engaged in transferring his section of the message to paper slips, which can afterwards be run through the transmitting apparatus, which can send the message at the rate of several hundred words per minute. Such a method is known as that of AUTOMATIC WORKING, one of the earliest and most successful being performed by the Wheatstone automatic transmitter. The message is transferred to a slip of paper by punching holes in it according to a definite system. Five steel punches, 1, 2, 3, 4, 5, are arranged to punch holes in a strip of paper as shown (Fig. 60), and three levers are arranged so that if one of them is depressed, punches 1, 2, 3, and 4 perforate the paper, corresponding to a dot as at *a*. The second lever depresses 1, 2, 4, and 5, and perforates the

paper as shown at *b*, this corresponding to a dash. The third lever punches 2 and 4 only, which are the spacing holes, by means of which the paper strip will be driven through the transmitter. The principle of the Wheatstone transmitter is illustrated in Fig. 61. The paper strip A, upon which the message has been punched, is driven forwards by means of a spur-wheel B, and the two thin rods or needles C and D are kept in vertical motion by the rocker E. The extent of their motion is limited by the paper strip, because they are arranged to come opposite the upper and lower rows of holes respectively in the strips.

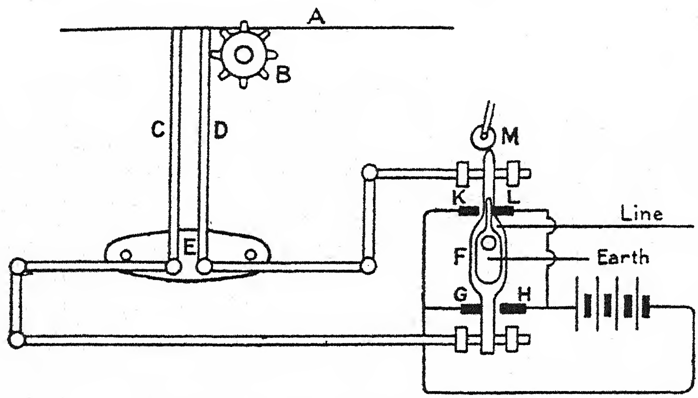


FIG. 61. Wheatstone automatic transmitter.

If, for example, D on travelling upwards passes through a hole in the strip, the lever F is pushed over, making contact at G, and a current is sent to the line, while the positive end of the battery is connected to earth through L. The rod C is placed half a space between the middle holes later than D, so that if on being driven upwards it finds a hole in the lower row (Fig. 60) corresponding to a dot, it passes through, and the travel of the lever pushes F over, so that contact is made at H and K, and a reverse current is sent to the line. If, however, a dash were being transmitted, the needle C would not encounter a hole in the strip until after a longer interval, so C could not travel upwards

and reverse the current in the line until a greater time had elapsed, and a dash would be indicated at the distant station. The double key enables reversals of current to be employed instead of a simple make and break, the stops K and L causing the earthing of that end of the battery which is not put to the line. The jockey wheel M ensures a firm pressure of the lever against the stops, and holds the lever in position until a reverse impulse is received.

One of the earliest telegraphic systems was that of Hughes, in which the letters of the alphabet were telegraphed directly. A wheel around which the letters are arranged is situated at each station. At the sending station the wheel is turned until the required letter is uppermost, which process sends a succession of currents to the line by means of stops, one stop corresponding to each letter. Thus for A one impulse is sent, for D four, for H eight, and so on. At the receiving station, an electromagnet moves the wheel forward one space for each current impulse, so that it brings the letter to the top corresponding to the letter at the sending station. This system is slow in working and soon gave place to the more rapid Morse system, but it is a sample of the kind of sending which can be adapted to print the message, for it is easy to arrange type round the wheel instead of depending upon visual reading.

Rapid systems for printing have since been devised which enable far greater use to be made of a line than could be attained even by the multiplex systems, for the message is printed automatically, without the necessity of reading by the operator. One of the most efficient and rapid systems is that of D. Murray, in which a machine resembling a typewriter punches a tape at the sending station and prints the message on a sheet or page at the receiving station. The speed of the printer is about 900 letters or 200 words a minute, and with five operators at each end, on the Murray system, about 200 telegrams an hour can be exchanged. On the Murray system, five spaces are

allotted to each letter and the holes are punched in these spaces, each corresponding to a letter. This is a development of the Baudot system, and has the advantage that every letter occupies the same length of the strip, as shown in Fig. 62. The transmitting apparatus resembles that of Wheatstone, but there is only one lever to pass

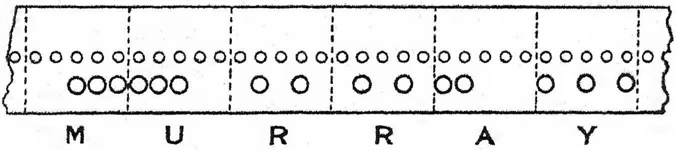


FIG. 62. Ribbon of Murray automatic printing telegraph.

through the holes in the strip. The star wheel B (Fig. 63) feeds forward the strip A. The needle C is attached to the horizontal thrust lever which has a tooth G on its under side. It is kept oscillating by the cam E, and when C travels upwards through a hole in the strip, the lever F is tilted so that it strikes the arm I and contact is made at

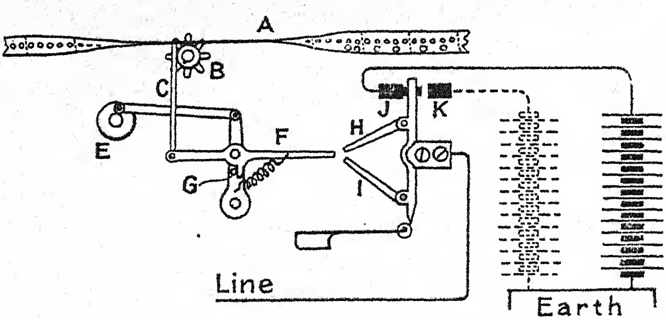


FIG. 63. Murray automatic transmitter.

J. If in the next oscillation C again passes through a hole, nothing further happens and the current to line continues; but if C should meet an unperforated part of the strip, the lever F is tilted and strikes the arm H, so that contact is broken at J and made at K, causing a reversal of the current in the line. The moving parts are driven by a synchronous electromotor whose speed is governed by a

vibrating reed very similar to an electrically driven tuning-fork (p. 27). At the receiving end, the current actuates the electro-magnet of a relay which punches holes in a strip, similar to those of the sending strip, and this strip is fed through a typewriter of a particular pattern. The five rods at A are driven all at the same time against the tape, and only those which fall upon holes pass through. Each rod A is attached to a bar cut out in a key-like form, and every combination of holes to form a letter in the strip brings one set of five slots in the bars vertically over each other, so that one of the vertical rods C can pass into these slots. Each rod C actuates one letter of the typewriter,

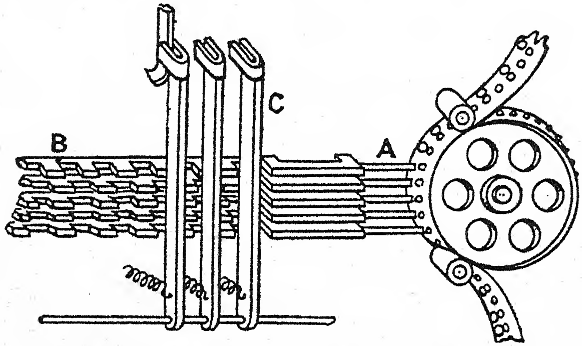


FIG. 64. Arrangement of keys for Murray telegraph printer.

which has the usual arrangement for feeding forward the paper. A general view of the Murray single-line transmitter is seen in Fig. 65 (Plate III). From this short survey it will be understood that the question of telegraphic printing is one of great mechanical complexity, and only the briefest of indications of the principles employed is attempted.

Submarine telegraphy is in these days so overshadowed by wireless telegraphy that we are apt to lose sight of its importance and of the tremendous impetus which its first successful development gave, not only to commerce, but to the science of electricity. It is perhaps impossible to close this chapter in a better way than by giving some account of the difficulties encountered and overcome in establishing

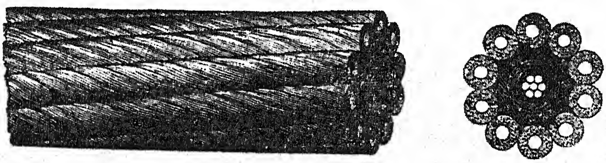
the first long-distance submarine telegraphic communication, namely that across the Atlantic Ocean. The early discoveries soon led to the erection of land lines of greater and greater length, so that by the middle of the last century the number of telegraphic installations was considerable, and short submarine cables were in successful use, that between Dover and Calais being laid in 1851. In October, 1856, the Atlantic Telegraph Company was formed, and the work of manufacture of the cable proceeded with, concessions from the British and the United States Governments being obtained and ships loaned. No single ship of that time could carry the whole cable, the weight of the one chosen being about 1 ton per mile. The British Government supplied H.M.S. *Agamemnon* and the United States Government the *Niagara*, each ship carrying part of the cable; the intention being that when one ship had completed the laying of its part of the cable, the parts should be spliced together in mid-Atlantic, and the other ship then complete the laying. The shore end was landed from the *Niagara* at Valentia on August 5, 1857, but after 330 nautical miles of cable had been laid the cable broke, owing to a faulty manipulation of the paying-out gear. The expedition was then given up for that year, and the ships returned to England. The second attempt to lay this cable was made in 1858, the same two ships sailing on June 10. On this occasion the plan was for both ships to proceed to mid-Atlantic, splice their two ends of the cable, and then one ship to lay the cable to Valentia, the other to lay its part to Newfoundland. The splice was made on June 26, but after several breaks occurred, both ships returned to Queenstown, leaving again for another attempt on July 17, and effecting the splice on July 29. On August 5 both ships completed the task, each laying its end of the cable, and at 3.55 p.m. on that day the first current was sent between the two continents.

Although not in charge of the scientific part of the undertaking, Lord Kelvin, then Prof. William Thomson,

was its real inspiration and guide. He it was who pointed out the electrical difficulties of signalling through very long submarine cables, and supplied the means of overcoming them. It was pointed out by him that a sharp variation in the value of the current would become blurred as it proceeded along the cable, owing to the effects of its resistance and its capacity (p. 123). Both resistance and capacity could be diminished by increasing the size of the cable, but this involves a great increase in cost, both of the cable itself and of its laying. Thomson, however, showed that an improvement could be made by earthing the end of the cable immediately after the sending of the current, and still more improvement by employing a reverse current before earthing. But the greatest improvement he made was in the type of instrument used for receiving the message. The electrician in charge of the Atlantic cable advocated the use of a heavy magnetic relay for observing the signals, and a very high electromotive force produced by an induction coil for sending. Thomson pointed out several objections to this method, and advocated a battery of ordinary cells for sending, and a delicate galvanometer for receiving. Had Thomson's advice been followed, there is little doubt that the Atlantic cable which was completed on August 5, 1858, would have rendered efficient service. But unfortunately the high voltage system was employed, with the result that the insulation of the cable rapidly deteriorated, and by October 20 the cable was entirely useless. Of the messages, numbering several hundred, which had been transmitted through the first Atlantic cable, every one had been received by Thomson's reflecting galvanometer.

Of the later and more successful attempt to lay an Atlantic cable little need be said. The ship *Great Eastern*, the largest vessel then afloat, was chartered for the purpose, being the only vessel capable of carrying the entire cable, which was heavier than the earlier cable, having a weight of 1·8 tons per nautical mile. On July 14, 1865,

the shore end of the cable was laid at Valentia, and the voyage begun. The cable broke, however, after 125 miles had been laid, and the *Great Eastern* returned. On July 13 of the following year, a new cable having been constructed, the *Great Eastern* started again, completing the journey on July 27. The task of picking up the broken cable of the previous year was then undertaken and completed successfully, and by September 8 the end of this second cable was safely landed at Newfoundland. The only great improvement in submarine telegraphy which followed was the employment of the siphon recorder, which has already been described. This rendered the speed of receiving much greater than could be attained by the



(*a*) (*b*)
Fig. 66. Submarine cable.

mirror galvanometer, and had the further advantage of producing a permanent and automatic record of the message.

The form of a submarine cable will be understood from Fig. 66, which represents an early form of Atlantic cable. Fig. 66 (*a*) shows the general view of the cable, and Fig. 66 (*b*) a cross-section. The core consists of 7 copper wires each of 1 millimetre diameter and embedded in gutta-percha, put on in layers. Then follows a layer of hemp and outside this a layer of steel wires each wire surrounded by hemp. The wires all run spirally along the cables. In modern cables more protective layers are used, and in shallow tropical seas, where certain submarine animals bore into the cable, a layer of brass tape surrounds the insulator. Galvanized iron wires give mechanical strength to the cable, and are prevented from corrosion by several protective layers of prepared tape.

CHAPTER VIII

The Telephone

WHEN the principal laws of the electric current have been elucidated, the applications in which the heating effect which is employed to render the filament of a lamp incandescent, and the forces of considerable magnitude met with in the electromotor cease to cause wonder, but in the case of the electric telephone the currents are so small and the mechanical movements reproduced are so minute that wonder at its success never grows less. Indeed, if the telephone were described to anyone without a demonstration of its performance, there is little doubt that it would be pronounced as unworkable. Nevertheless, Alexander Graham Bell, in 1876, after many failures, succeeded in showing that sounds occurring at one place could be reproduced at another by means of a very simple device. In fact, the method adopted by Bell is still used, in an almost identical form, in all telephone receivers. Later experimenters have altered the design, but have not added any new principle to the Bell receiver.

On causing the poles N, S of a permanent magnet (Fig. 67) to approach a thin sheet of iron AB, many of the magnetic lines of force from the poles pass on to and through the iron sheet, and this we recognise as the condition for N to attract the iron sheet or diaphragm at A, and S to attract the part at B. When AB is very close to the poles of the magnet there is an easy magnetic path from pole to pole through the iron diaphragm, and when AB is far away there is a considerable length of air path present in addition to the path in the iron. In the former case there will be more lines of force present than in the latter. Hence, if AB is moved to and fro, the number

of magnetic lines of force will vary. Since these lines all pass down the iron magnet, they must also pass through the two coils C and D, wound round the tips of the poles, and because their number is continually varying, electromotive forces and, if the circuit CD is complete electrically, currents are produced in these coils. Another way of looking at it is to consider that magnetic poles are produced on the iron diaphragm due to the proximity of N and S, and if the diaphragm now vibrates, these poles are continually approaching and receding from the coils CD. This is the condition for currents to be produced in CD, as was seen in the experiment illustrated in Fig. 20.

In the act of speech, or any other production of sound,

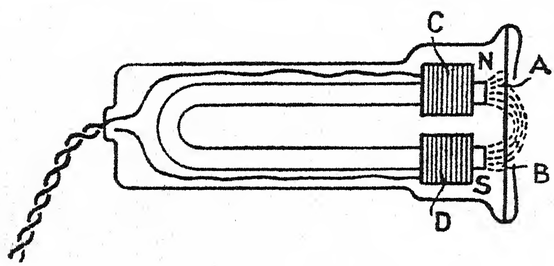


Fig. 67. Bell telephone.

the air is continually being compressed and rarefied. Every time that the air is compressed, a state of compression travels forwards, and every time that it is rarefied a state of rarefaction travels forwards. Thus, during the production of sound, waves of compression and rarefaction are produced by the sounding body. These waves, falling upon the drum of the ear, set it in motion; the compressions drive it in and the rarefactions draw it out. When the drum of the ear is caused to vibrate, the inner mechanism of the ear, together with the auditory nerve, convey the sensation to the brain which we call "sound," but how this physiological process of the inner ear is carried out does not here concern us.

The diaphragm AB of the telephone behaves in a

similar manner to the drum of the ear, being driven in by the compression in the sound waves and drawn out by the rarefactions. This motion, as has been seen, causes currents in the coils CD. The instrument is known as the TRANSMITTER, and its function is to produce variations in electric current in the coils CD, corresponding to the compressions and rarefactions of the sound wave falling upon the diaphragm. These variations of current are very small, and would be difficult to detect without a similar piece of apparatus whose function is to effect a transformation back into sound waves. This instrument is called the RECEIVER, and is similar in all respects to the Bell transmitter (Fig. 67). Its action is simpler to understand than that of the transmitter; for the coils on the tips of the magnets are connected in series with the similar coils CD of the transmitter by means of the line or cable connecting the transmitting and receiving stations. Hence the same currents and variations in current occur in the coils of both instruments. One direction of the current increases the strength of the magnetic poles N and S and the diaphragm is pulled in. As the current becomes weaker, or is reversed, the poles are weakened and the elasticity of the diaphragm itself causes it to recover and hence to move outwards. Thus it is kept vibrating at a rate similar to that of the diaphragm of the transmitter, and it therefore sets up waves which have the same frequency as the sound waves which fell upon the transmitter. In this way the sounds are reproduced. A Bell receiver is shown in Fig. 68, in which a bar magnet M is used, the coil being a flat bobbin BB. D is the diaphragm, LL the leads of the coil, and E a conical mouthpiece.

The only great alteration of the telephone from the above described type is due to the introduction of the principle of the CARBON MICROPHONE of D. E. Hughes (1877). If two pieces of carbon are placed in contact, a current can flow from one to the other through the contact. But on varying the pressure between the two carbons, the

resistance changes. Increasing the pressure causes a drop in the resistance. Consequently if the carbons are part of an electric circuit of low resistance, which includes a cell or battery, variation in the pressure of the carbon contact will cause comparatively large variations of the current in the

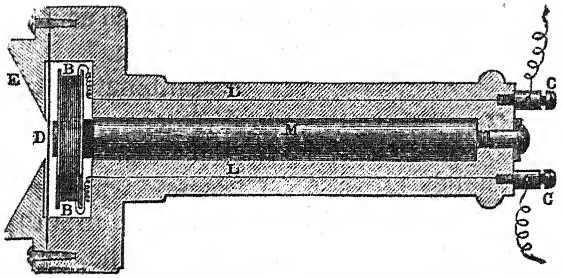


FIG. 68. Bell telephone receiver.

circuit. This may be demonstrated in a manner shown in Fig. 69, in which a carbon block AB with pointed ends rests between two other carbon blocks C and D. This arrangement is situated in a current circuit with the cell G and a Bell telephone receiver R. Any slight mechanical disturbance of AB causes a sound to be heard in the receiver. The mechanical disturbance causes variation in pressure between the carbon surfaces in contact at A and B, with consequent variation in electrical resistance, thus causing the current in the circuit to change, with production of motion of the diaphragm of the receiver. So sensitive is this arrangement that if a watch be placed on the carbon block C its ticking can be heard in the receiver R, although this may be a considerable distance from C.

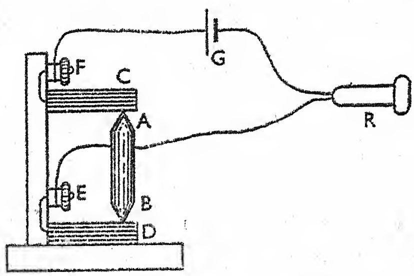


FIG. 69. Carbon microphone.

Although the contacts between the carbons of Fig. 69

are fairly sensitive, they are somewhat unreliable, and are apt to lose their sensitiveness from time to time and to require readjustment. It is customary, therefore, in modern telephones to replace the single contact by a multiple contact, by employing carbon granules or pellets situated between a thin carbon diaphragm and a carbon block, in constructing a microphone for use as a telephonic transmission.

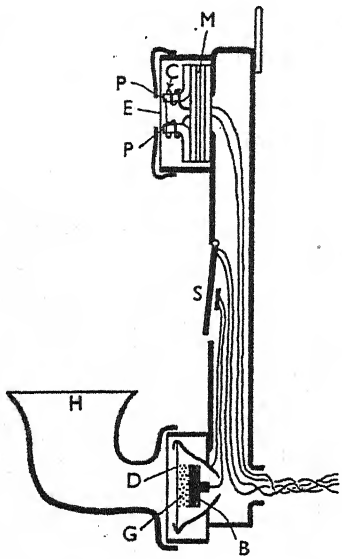


FIG. 70. Hand set—combined receiver and transmitter.

A combination transmitter and receiver as commonly used is illustrated in Fig. 70. The sound waves entering by the ebonite mouthpiece H fall upon the carbon diaphragm D. This is situated at a short distance from the carbon block B, and electrical contact takes place between them through a number of carbon pellets or granules G. The movement of the diaphragm causes variations in the contacts between the granules and so varies the current. If the granules become wedged together and the transmitter so loses its sensitiveness, a shake given to the instrument will usually restore it to proper working condition.

The receiver in Fig. 70 deserves notice, as it is of a very efficient form. The permanent magnets M are rings of hard steel, so magnetised that the opposite ends of a diameter, where the soft-iron horns PP are attached, are respectively N and S poles. This maintains the soft-iron horns PP in a state of magnetisation, one being a N pole and the other a S. The iron diaphragm nearly touches PP, and the coils C connected with the transmitter at the

distant station are wound upon these pole pieces. The variation of the current in these coils causes the motion of the diaphragm E, as in the original Bell receiver. It was known quite early in telephone practice that the iron core upon which the coils were wound should be permanently magnetised, either by means of a current flowing continuously, or by means of a permanent magnet. The latter is the more economical means, because it does not involve the continual expenditure of energy; and further, the wires which will carry the feeble varying current used in the reproduction of sound would have to be increased considerably in thickness if the much greater current required to produce magnetisation of the iron core had to be carried.

The reason for the permanent magnetisation is not far to seek. It is clear that the amount of movement of the diaphragm must be great for the production of loud sounds, and that the movement of the diaphragm is proportional to the VARIATION of the force between the poles of the magnet and the diaphragm. The force itself is proportional to the product of the pole strength of the magnet and the induced pole strength on the diaphragm produced by the magnet. Hence the variation in pull is ultimately proportional to the variation of the *square* of the pole strength of the magnet. Now the variation of the square of a quantity is greater, the greater the quantity itself, so that to get a large motion of the diaphragm, the magnetisation must be great to begin with. For this reason the permanent magnet is always employed, so that feeble variation in the current in the coil will produce relatively large motion of the diaphragm.

The actual motion of the diaphragm in order to produce audible sounds is surprisingly small. It was shown by the late Lord Rayleigh that the motion to and fro of the particles of the air for the production of an audible sound did not exceed 0·00000008 centimetre, or 0·00000003 of an inch.

For many years there was hardly any other form of

telephone receiver used than the Bell type, but several loud-speaking telephones have since been devised. The "Brown loud speaker," made by Messrs. S. G. Brown, Ltd., is an instrument of this type. In this form the electro-magnet does not influence the diaphragm directly, but is placed under a reed A (Fig. 71) which is attached to the bottom of a conical diaphragm B, immediately under the large horn or trumpet C. The reed is acted upon by the electro-magnet M, the windings of which carry the current. This form is largely used in wireless telegraphy, and enables the sounds received to be heard by a number of people simultaneously.

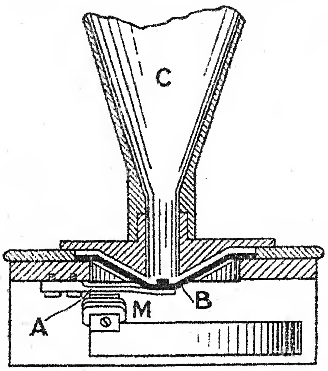


FIG. 71. S. G. Brown loud speaker.

Loud speakers of this type have been largely superseded by the moving-coil loud speaker, which reproduces the transmitted sounds more accurately and with less distortion. This consists of an electro-magnet A, with its coil B and the conical diaphragm C, which carries a small coil D, free to move backwards and forwards in the space E. The coil B of the electro-magnet carries a steady current: if an alternating current is applied to the coil D it will oscillate backwards and forwards carrying the cone with it. In the case of a wireless loud speaker, the output current of the receiver is applied through a transformer to the coil D causing the cone C to move backwards and forwards to reproduce the sound.

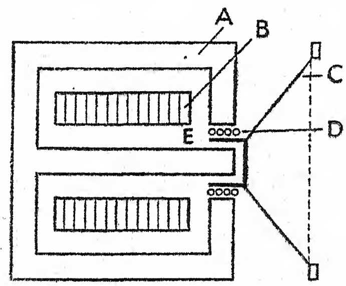


FIG. 72. Moving-coil loud speaker.

An extremely important modification of the telephone system, which has resulted in the extension of the distance over which telephony is effective, consists in the application of the transformer. Since the loudness of the reproduction depends upon the variation in current in the circuit, and this again depends upon the variation in resistance at the microphone contact, it follows that if the resistance at the contact is a small part of the whole resistance of the circuit, any variation in it cannot make a large variation in the resistance of the whole circuit. It follows that the current changes produced by the microphone are too small to produce efficient transmission when the length of the cable connecting the two stations is so great that its resistance is considerable. By interposing a transformer, the micro-

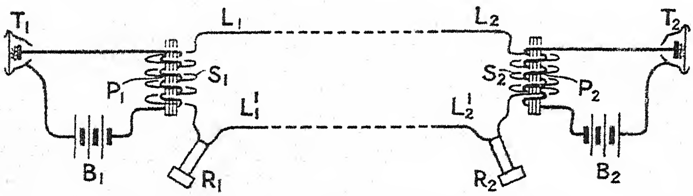


FIG. 73. Telephonic circuits with induction coils.

phone circuit and the receiver circuits are separated, so that the above objection no longer applies.

Let P_1S_1 (Fig. 73) be a small transformer (p. 56), of which the primary coil P_1 is in series with the carbon microphone T_1 and battery B_1. On speaking into T_1, variations in current are produced in P_1, and therefore varying electromotive forces arise in S_1 and produce varying currents in the secondary circuit $S_1L_1L_2S_2R_2L'_2L'_1R_1$ in which the telephone receivers R_1 and R_2 are included. The lines L_1L_2 and $L'_1L'_2$ may be a twin wire connecting the two stations, or in some cases, $L'_1L'_2$ is an "earth return," that is, the circuit at L'_1 and L'_2 is connected to some conductor in good contact with the ground, such as a water supply pipe, in which case the circuit is completed through the earth itself.

It will be seen that the primary circuits $T_1P_1B_1$ and $T_2P_2B_2$ are both local and of low resistance, which is the condition for most efficient working of the microphone. The high resistance of the line connecting the stations is now of little objection, since it is in the circuit of the secondary coil of the transformer, which always has a fairly high resistance, and the receiver, which may now also have a fairly high resistance. With a system such as this, telephony is carried on with efficiency over distances of several hundreds of miles.

In order to render telephonic service convenient, devices for switching in an electric bell instead of the microphone circuit, by the act of hanging up the receiver, and for

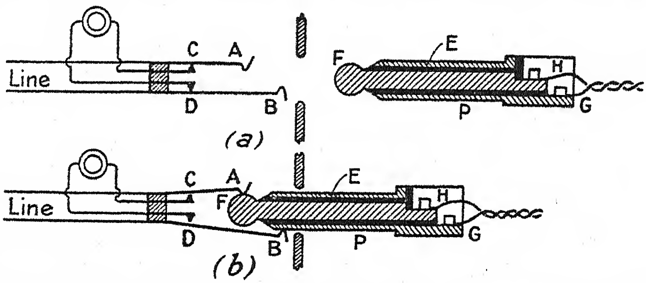


FIG. 74. Plug and jack for telephone exchange.

ringing up the distant station, are employed. Also central exchange systems have come into common use, where the instruments for many subscribers are connected to one central point, so that any one subscriber can be put into communication with any other. Also trunk lines connect distant exchanges with each other. The various systems by which these exchanges are worked do not involve any new principle, and only one of the special devices for inter-communication between subscribers will be described here. This is the JACK AND PLUG shown in Fig. 74. The lines from a subscriber's instrument are attached to two springs A and B, which make contact with C and D when the plug P is not inserted. C and D are connected with some form of indicator, either bell, buzzer, or small electric lamp, at

the exchange, which is actuated when the subscriber lifts his receiver from its hook. The plug has two conducting parts E and F, separated by a sleeve of ebonite, shown black in the diagram. Of the leads attached to the plug, H is connected to F and G to E, and these leads go to a similar plug at the other end of the short piece of flexible twin wire. When the subscriber "rings up" the exchange and asks for a particular number, the exchange operator puts the plug P into the jack as shown in Fig. 74 (*b*), F makes contact with A and E with B, and A and B are at the same time lifted from the contacts C and D. A similar plug attached to G and H performs a like operation at the end of the line of the subscriber who is called up, and the two subscribers are now in communication through the exchange.

Hand-operated exchanges are now largely replaced by automatic: the caller operates a dial which through an electromagnet moves a travelling contact over a series of fixed contacts to engage that which corresponds to the number dialled, thereby completing the desired circuit and causing a bell to ring in the instrument of the person who is being telephoned.

The subject of wireless telephony will be left to Chapter X, on wireless telegraphy.

One of the most difficult problems facing the telephonic engineer is that presented by DISTORTION, or the change in the character of the waves travelling along a line, so that the movement of the diaphragm of the receiving instrument is not a faithful copy of that of the transmitting diaphragm. In order to understand this point, it must be realized that speech consists of a very complicated motion of the air in the cavities of the throat and mouth of the speaker. This motion is the sum or resultant of several simpler motions, each constituting a note or sound of definite frequency or pitch. To take first a case which is much simpler than that of the human voice, consider a stretched string, such as that of a piano or a violin. Any given string, when

plucked or struck, vibrates at a given rate, and starts air waves at the same rate, by means of which we hear it and recognise the pitch. The middle C of the piano corresponds to 256 vibrations per second, which is called its FREQUENCY. The octave lower is produced by a frequency of half this, or 128 vibrations per second, and the octave higher by double, or 512 vibrations per second, and so on for the other notes. But a string does not as a rule vibrate in one piece only, the two halves vibrate with double the frequency of the string vibrating as a whole, and the thirds and quarters and so on vibrate at three times and four times the frequency respectively, so that, in the case of an actual string, the sound heard by the ear is very complicated. The harmonics, or overtones, as they are called, which are produced by the vibration of the segments of the string, give character or quality to the note, and it is by means of them that we recognise the note as being due to a string, or a tuning-fork, or an organ pipe, as the case may be. The ear has such a delicate sense of perception that two or more instruments sounding the same note at the same time can be recognised, and even their quality appreciated. Still greater is the complexity in the case of the human voice. Each sound, such as a vowel, or a consonant sound, has definite pitch, but is so rich in overtones that it can be recognised by means of them. In order to transmit speech by telephone, the variations of current in the line must correspond exactly to the movements in the air which constitute the sound. In Fig. 75 (*a*) is shown a curve which gives the current in a telephone wire when the word "pea" is pronounced; the scale at the side shows that the current never reaches 10 micro-amperes, a micro-ampere being one-millionth of an ampere.

Following the quiescent stage 1 is a sudden or explosive sound at 2, corresponding to the consonant "p," and 3 is the vowel or "ee" sound. Similarly at Fig. 75 (*b*) is shown the current for the sound "f." Each of these consists of a particular mixture of notes of various frequencies, and

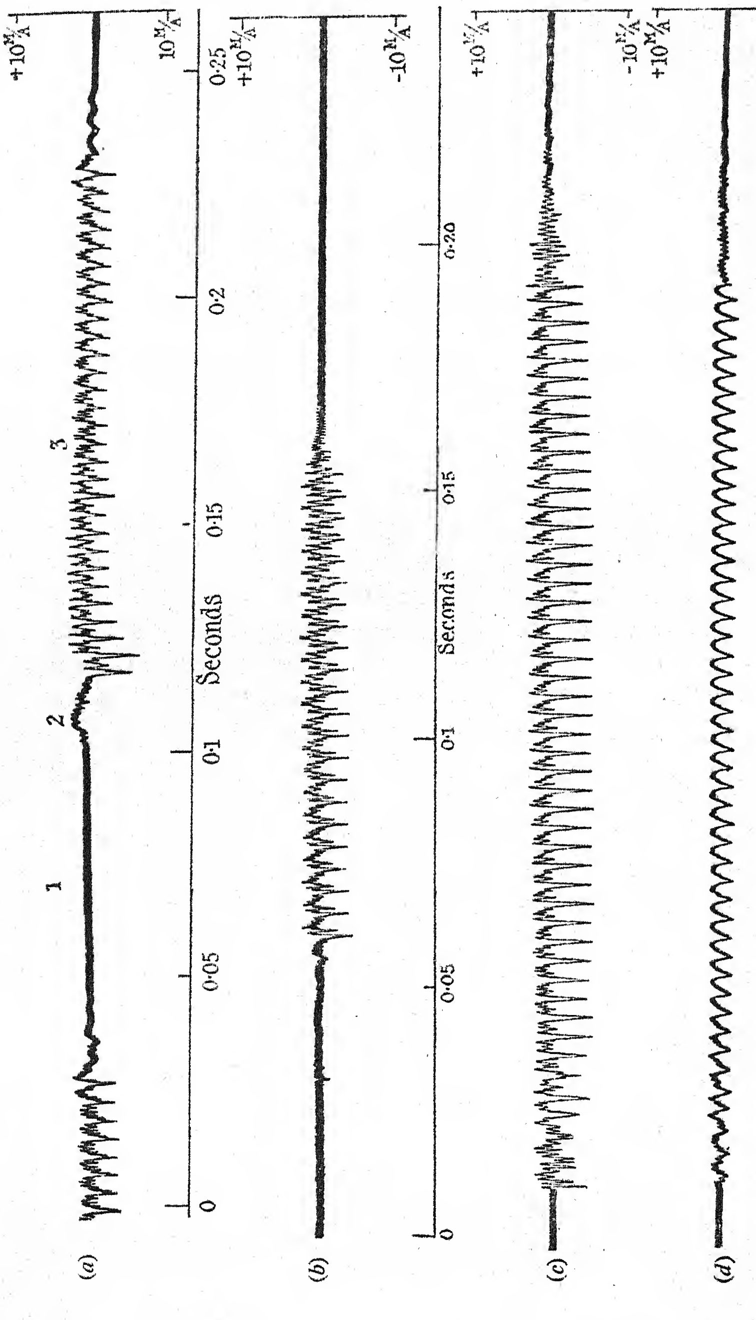


FIG. 75. Current curves for vowel sounds transmitted by telephone.

[*From Hill's "Telephonic Transmission."*

although the eye does not recognise the shapes of the curves, the ear would recognise the sounds when the diaphragm of the receiver vibrates in accordance with these variations of current.

Now, in the process of transmission along a telephonic wire, every current dies away with increasing distance from the sending station, that is, the currents become *attenuated.* Generally speaking, the attenuation depends upon the frequency of the variations of current, so that on arrival at the receiving station, the various components of the original current are attenuated to different extents, and the resulting sound differs in quality from that transmitted. This distortion is usually only slight on telephone lines covering short distances, but becomes considerable with the use of underground cables or submarine cables. In Fig. 75 (*c*) is seen the current curve at the sending end of a telephone cable, and (*d*) is the corresponding current at the end of the unloaded cable twenty miles in length. A glance at these two curves will make it clear that a great deal of the finer or more rapid vibration has been lost in transmission. When the distances are very great, the distortion renders the recognition of speech impossible.

The law according to which oscillations in a current propagated along a wire or cable die away is one which is frequently met with in physical problems. It is the "compound interest" law, which is, that the rate of the change occurring in any quantity is proportional to the value of the quantity. If an oscillation dies to half its value in a 100-mile cable, it will halve again, or fall to one-quarter in the next hundred miles, and to one-eighth of the original value in the next hundred miles, and so on. This attenuation is, of course, common to all modes of propagation of waves, although the law of attenuation is not always the same. For example, in the case of sound waves or light waves, which spread out in all directions, the intensity falls off inversely as the square of the distance. In wireless waves, which spread out over the surface of the earth, the

falling off is nearly inversely as the distance; but in the case of waves of current passing along a wire, such as a telegraph or telephone cable there is no actual spreading out, but there is a leakage through the insulation of the cable, and a dissipation of energy owing to the electrical resistance of the wire. Hence the higher the conductivity of the cable the less will be the attenuation.

In order to calculate the velocity of transmission of variation of current along a cable, and the attenuation of the variations, considerable mathematical analysis is necessary. These quantities were first calculated by Lord Kelvin in 1855, but he omitted certain important quantities. The complete calculation was given by Oliver Heaviside in 1887, when he pointed out that with a certain relation between the resistance, capacity, leakage, and magnetic effect, the attenuation of the waves is the same for all frequencies. It follows that if this condition can be attained, there will be no distortion, for all the frequencies in the original sound will preserve their original proportion in the wave, however far it is propagated along the cable, since the oscillations of all frequencies will be attenuated to the same extent.

The required relation between the constants of the cable for distortionless transmission is disturbed in the case of most cables, particularly underground and submarine cables, by the electric capacity being disproportionately great with reference to the magnetic effect. The capacity cannot very well be reduced, but there are many devices for increasing the magnetic effect of the current. One of these is to wind iron wire round the cable, because the magnetic effect is greater with iron surrounding the current than when no magnetic material is present, as we have seen in Chapter II. This method has many advantages, but there is one great disadvantage, the size and weight, and therefore the cost, of the cable are considerably increased. Another method, which has met with considerable success, is to place iron-cored coils in the cable at regular intervals, and it was shown by Prof. M. I. Pupin in 1899 that the

advantages of continuous loading may still be obtained, although the loading is now to be done at separate points. A box of coils, such as is used in the United Kingdom for underground cables, is illustrated in Fig. 76, with the

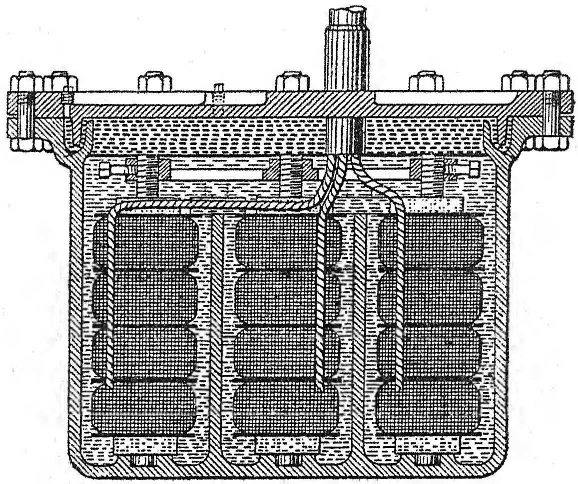


FIG. 76. Loading coils.

winding of the separate coils (Fig. 77). The cases may contain coils for 98 lines, but it is preferable not to exceed 50. The lines are collected and brought out of the case all

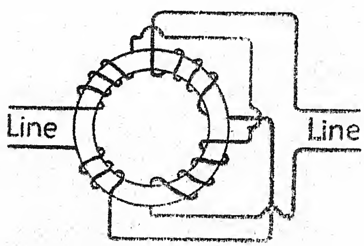


FIG. 77. Arrangement for magnetic balancing of loading coil.

together, where they are jointed to the cable. Such loading or "Pupin" coils are placed at intervals of several miles, and their use has vastly increased the distances over which clear and recognisable speech can be transmitted.

It would clearly be very desirable to reinforce the telephonic currents at points on the line at which, owing to distance, the currents have become very feeble. This was attempted without success by many forms of relay, but none was successful until the introduction of the triode tube was developed for use in wireless telegraphy. A description of the triode is necessarily postponed to Chapter X. It has now become a common practice to transmit by cable-telephone to a wireless station, where the telephone currents actuate the wireless set, the wireless waves covering hundreds of miles of sea and being eventually transformed to ordinary cable currents, thus completing the travel between towns in far distant countries.

CHAPTER IX

Electrolysis and Batteries

THE early history of electrolysis may be identified with that of current electricity, and has already been outlined in Chapter I. Volta's discovery of the production of current by his "pile" opened the discussion as to the origin of the electric charges produced; that is, whether they are produced by chemical means or by the mere contact of dissimilar metals. But this discussion is now of academic interest only. The discovery of Nicholson and Carlisle was the beginning of the actual study of electrolysis and many investigators examined its phenomena under various conditions. In particular, the first separation of the metals sodium and potassium by Sir Humphry Davy, in 1807, should be noticed. The nature of soda and potash were not known until Davy, applying a battery of 250 cells to the fused salt, obtained a small globule of soft metallic substance which burned readily in air, with a yellow flame in the case of the metal from soda, and a violet flame in that of the metal from the potash.

Passing on, the next notable investigation was that of Faraday, which placed our knowledge of the quantitative laws of electrolysis in the form which is still held to be valid. One hundred years have elapsed since the statement of these laws by Faraday, but they still represent the truth, to the highest order of accuracy of measurement of which we are now capable. Faraday's laws of electrolysis are two in number, the first stating that the amount of any electrolye decomposed by the passage of a current is proportional to the quantity of electricity which passes. Whether a small current flows for a long time or a strong current for a short time does not matter, the amount

of chemical effect is proportional to the product of current and time, which measures the amount of electricity which passes. Thus—

$$\text{Quantity of electricity} = \text{current} \times \text{time}.$$

Since the practical unit of electricity is called the COULOMB, this relation may be written in the form—

$$\text{Number of coulombs of electricity passing in a circuit} = \text{current in amperes} \times \text{time in seconds}.$$

The second law of Faraday refers to the effect observed when different materials are used as electrolytes, and states that the amount of substance liberated by a given quantity of electricity passing through the electrolyte is proportional to the chemical equivalent of the substance. This law is of far-reaching importance, and it is worth while to consider it carefully. Chemistry, as a modern science, is built up on the theory that matter consists of atoms of about ninety different types, each type corresponding to an ELEMENT. The atom of hydrogen is the lightest, and calling its weight unity, that of the atom of the element oxygen has weight 16, copper 63·6, chlorine 35·5, silver 108, sodium 23, zinc 65·4, and sulphur 32. These numbers are only approximate; their values as found by the latest determinations need not concern us here. Since no quantity of matter less than an atom can take part in any chemical process, the simplest form of a compound of, say, sodium and chlorine, is represented by the formula $NaCl$, Na representing an atom of sodium or natrium, and Cl an atom of chlorine. From the numbers given above, sodium chloride ($NaCl$) consists of sodium and chlorine in the proportions 23 of sodium to 35·5 of chlorine by weight. Similarly, hydrochloric acid (HCl) consists of hydrogen and chlorine in the proportion 1 of hydrogen to 35·5 of chlorine, since each atom of hydrogen combines with one atom of chlorine. Hydrogen, chlorine, sodium, etc., are called mono-valent elements, because each atom of one combines with one atom of the other. But some substances are

di-valent, that is, an atom combines with two mono-valent atoms. Thus, water (H_2O) consists of hydrogen and oxygen in the proportion 2 by weight of hydrogen to 16 by weight of oxygen, or two atoms of hydrogen to one of oxygen, and we see that oxygen is a di-valent element. Similarly, copper and zinc are di-valent, while silver is mono-valent. Now the chemical equivalent of a substance is the weight of it which can combine with 1 gramme of hydrogen, or with the amount of any substance that would combine with 1 gramme of hydrogen. Thus the chemical equivalent of chlorine is 35·5 and of sodium 23, since 35·5 grammes of chlorine would combine with 1 gramme of hydrogen, and 23 grammes of sodium would combine with 35·5 grammes of chlorine. On the other hand, if we take the case of copper or of zinc, copper chloride ($CuCl_2$) and zinc chloride ($ZnCl_2$) indicate that an atom of copper or of zinc is di-valent, and the chemical equivalent of copper is not 63·6, but half of this, or 31·8, and of zinc 65·4/2 or 32·7. It must not be forgotten that radicles can act as elements; thus in nitric acid (HNO_3), NO_3 is mono-valent, with a chemical equivalent of 14+48 or 62, while in sulphuric acid (H_2SO_4), SO_4 is di-valent, with a chemical equivalent of (32+64)/2 or 48. Thus the second law of electrolysis, as given by Faraday, means that the current which, in a given time, would liberate 1 gramme of hydrogen, would also liberate 8 grammes of oxygen, 108 grammes of silver, 23 grammes of sodium, 62 grammes of NO_3, 48 grammes of SO_4, 31·8 grammes of copper, or 32·7 grammes of zinc. This may be represented in a simple manner, as in Fig. 78. The vessels contain solutions of hydrochloric acid, silver nitrate, sulphuric acid, and copper sulphate. Then, since the cells are all in series, it is clear that the quantity of electricity which passes through all the cells is the same; for the current must be the same in them all, and the time for which the current flows must be the same for them all. It follows from Faraday's second law that if the current flows until 1 gramme of hydrogen is liberated in any one of them,

then for every cell in which hydrogen is liberated, 1 gramme will also be the amount, and in the other cases, the amounts liberated will be the chemical equivalents of the respective substances. Of course, the substance liberated may or may not retain its form. Thus, the copper or silver would remain as copper or silver coatings of the electrode. Hydrogen would bubble away as gas, but SO_4 would attack the electrode and form a sulphate, or attack the water and form a gas, as explained on p. 15.

Faraday himself saw that the two laws of electricity which he enunciated were the expression of some deep-seated law, and that when the facts of electrolysis became more clearly understood, our knowledge of the constitution of matter would at the same time be widened. For the

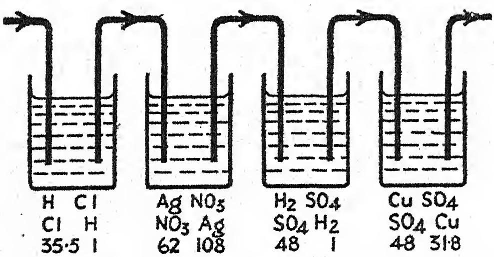


Fig. 78. Electrolytic cells representing the laws of electrolytes.

laws of electrolysis may be put in another form, which is more striking, but is not so useful for the everyday purposes of calculation, namely, that every mono-valent atom carries the same amount of electricity, which therefore appears to be a natural fundamental quantity; every di-valent atom twice this amount, every tri-valent atom three times this amount, and so on. This follows from the fact that the atomic weights of the mono-valent atoms are their chemical equivalents, the atomic weights of the di-valent atoms are twice their chemical equivalents, etc.

All substances in their usual state are neutral as regards electricity, but mono-valent atoms can acquire a positive or a negative charge of electricity, and in the solution are

driven by the electric field, established by the external battery or dynamo, towards the cathode if the charge they possess is positive, as in the case of hydrogen or the metals, and in the opposite direction, that is towards the anode, if the charge is negative, as in the case of the acid radicle. It is thus seen that the current in the electrolyte consists of two drifts of atoms, positively charged atoms towards the cathode and negatively charged atoms towards the anode. That this is the explanation of the process of electrolysis we owe to Svante Arrhenius (1887), who considered that the compound in solution was partially or wholly dissociated or split up into its atoms or radicles, which possessed charges in accordance with Faraday's laws, and that when these charged atoms arrived at the conducting electrodes, the charges were given up to the electrodes, while the atoms again acquired their ordinary neutral condition. This dissociation theory soon replaced the older theories, in which it was considered that the compound was actually split up in the process of electrolysis. The work of J. H. van 't Hoff, W. Hittorf and others filled in the details of the dissociation theory. The strongest support followed from the facts that other and non-electrical methods showed that the number of particles in the solution was in excess of the number of actual molecules of the substance dissolved, the excess being produced by the dissociation of some of the molecules into the constituent atoms.

One of the most important uses of our knowledge of electrolysis is the application to the measurement of electric current. A consideration of Faraday's laws of electrolysis shows us at once that if the actual amount of any one substance liberated by a known current in a known time can be found, the amount of the same substance liberated by any other current in any time can be calculated, and the amount of any other substance liberated can be found from a knowledge of the chemical equivalent. For this purpose it is useful to reduce the current to one ampere and the time to one second, and to give a name to the quantity of

any substance liberated. This quantity is called the ELECTRO-CHEMICAL EQUIVALENT of the substance. The electro-chemical equivalents of the different substances are, from Faraday's second law of electrolysis, proportional to their chemical equivalents, and it is of the utmost importance to determine once for all, as accurately as possible, the electro-chemical equivalent of some substance. This determination was undertaken by Lord Rayleigh and Mrs. Sidgwick in 1884, the substance chosen being silver. The choice fell upon silver for several reasons. Silver has the largest known electro-chemical equivalent, having a fairly

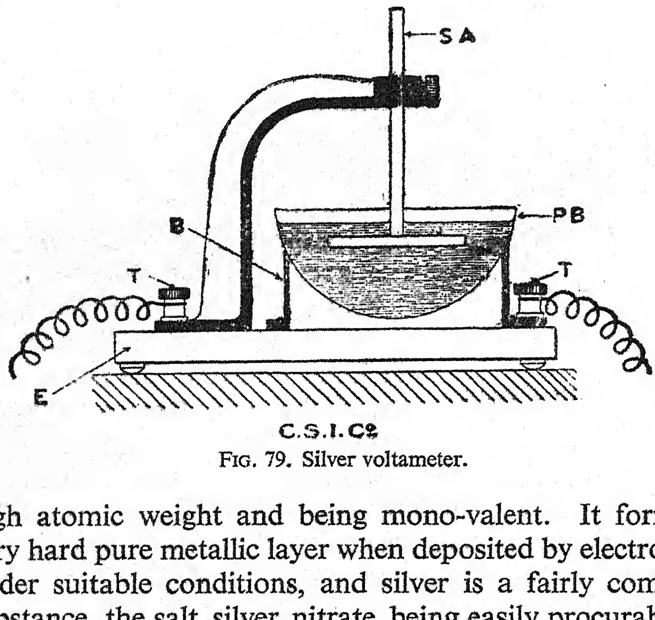


FIG. 79. Silver voltameter.

high atomic weight and being mono-valent. It forms a very hard pure metallic layer when deposited by electrolysis under suitable conditions, and silver is a fairly common substance, the salt silver nitrate being easily procurable in a fairly pure form. The apparatus used in the measurement of electric current or the determination of the electro-chemical equivalent is called the VOLTAMETER, and the form of the silver voltameter usually employed is shown in Fig. 79. PB is a platinum dish or basin supported upon a conducting base B and containing a solution of silver nitrate. A plate of silver is immersed in the solution, being

carried by the rod SA. T and T are the terminals by which the current enters and leaves. The current enters the solution by the plate, which is therefore the anode, and the platinum dish is the cathode, and receives the deposit of silver. The dish is first cleaned with nitric acid, washed, dried, and weighed. The time for which the current passes is noted, and on the cessation of the current the basin is again washed in pure water, dried, and weighed. The increase in weight is the weight of the silver deposited, and in Lord Rayleigh's experiment the current was determined by means of a current balance in which the force between two coils carrying the current is found by weighing. From these data the electro-chemical equivalent of silver was found to be 0·001118 gramme per ampere per second. Later determinations have shown it to be 0·00111827. Once the electro-chemical equivalent is known, the method of the voltameter may be used for the measurement of current. The experiment is carried out exactly as before, but instead of calculating the electro-chemical equivalent from the known current, the order is reversed, the current being calculated from the known electro-chemical equivalent. This method is extremely useful and is generally employed in the standardisation of current-measuring instruments such as the ammeter. When the accuracy required is not very great, the copper voltameter may be used. Three copper plates supported by metallic rods carried by wooden supports AB, Fig. 80, dip into a solution of copper sulphate. The outer pair of plates acts as anode and the middle plate as cathode. The washing and weighing is carried out as in the case of the silver voltameter, and the process is similar.

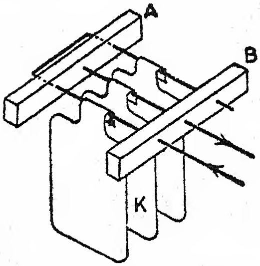


FIG. 80. Plates of copper voltameter.

Many industrial processes are founded upon the phenomenon of the electro-deposition of one metal upon another, generally a rare metal upon a common one. This may be

for the purpose of ornament or for preservation. The innumerable instances in which silver is deposited upon the commoner metals need only be mentioned, electroplated, or "plated" goods being very common. In electroplating, the chief necessity is to produce a hard adhesive coat, which, in the case of silver, is matt or rough, but may easily be burnished, to give the ordinary bright metallic lustre. To ensure a hard deposit, care must be taken that the current is not too strong, or the metal will form a soft and friable layer which is useless. Also perfect adhesion depends upon the thoroughness of the cleaning of the article which is to be electroplated, scrubbing with sand or scratching with a wire brush being the most effective methods of preparing the surface, from which all trace of grease must be removed. The electrolyte itself is a solution of the double cyanide of silver and potassium, made by adding a solution of potassium cyanide to a solution of silver nitrate until the heavy white precipitate, which is formed at first, completely disappears, giving a clear solution ready for electroplating. The article to be plated, after being carefully cleaned, is hung up in the solution by a wire and connected to the negative terminal of a battery, so that the current leaves the electroplating bath by way of the article, which therefore acts as the cathode. The anode should be a plate of silver, so that as silver is deposited upon the article fresh silver goes into solution, and the strength of the bath does not change. Electro-gilding is carried out in a manner similar to that of electro-silvering, the solution in this case consisting of 1 part of gold chloride to 10 parts of potassium cyanide to 200 parts of water. Silver and bronze are easily gilt, but to gild iron, zinc, or tin it is necessary first to deposit a layer of copper, then upon this to deposit the gold.

Several other metals are used, to a limited extent, for plating, among which may be mentioned nickel, on account of its protective property, zinc, and even brass. By employing both copper and zinc in solution as the electrolyte

and an anode of brass, the two metals may be deposited upon iron or steel articles, and form a layer which effectually prevents rusting. The electro-deposition of brass is much more difficult than that of the pure metals, but by regulating the process carefully, a red brass, rich in copper, or a pale brass, rich in zinc, may be deposited.

By far the most important of all electrolytic processes is the deposition of copper, either for the effect of the deposited layer, or for the purpose of refining the copper. In the manufacture of copper conductors for carrying the electric current, it is of the utmost importance that a high degree of purity in the metal should be attained; for a very small percentage of impurity will increase the electrical resistivity of the metal to a large extent, causing considerable waste of energy in carrying the current. It so happens that when impure copper is used as anode in an electrolytic cell of copper sulphate, the copper only goes into solution, the impurities merely dropping out as the copper is dissolved, and forming a slime or mud at the bottom of the electrolytic bath. Since silver and gold are two of the impurities commonly occurring in raw copper, the recovery of these metals from the mud deposited is a matter of considerable profit. For the cathode, a strip of pure copper is used, and the deposit upon it, being copper of great purity, is in the form desirable for the manufacture of electrical conductors. A large proportion of the copper used in the world is now purified electrolytically.

An interesting application of this process is the making of copper tubes invented by S. Cowper-Coles. If the copper be deposited upon a brass tube carried by a mandrel which is rotated at about 1000 revolutions per minute, the centrifugal action and the friction of the liquid remove all solid impurities as well as bubbles. In this way very satisfactory tubes may be made, and, if required, the tubes may be slit and opened out to form sheet.

Another important use of the electro-deposition of copper is the covering of iron or steel articles for the pre-

vention of rust, or as a preliminary coating upon which one of the harder non-corrodible metals may be deposited; but the process of the most importance of all is that of electrotyping. When a book is to be printed, a vast amount of type has to be set up, and the formes containing type, and probably diagrams, are very bulky. It is therefore usual to electrotype them, that is, make duplicates in the form of copper impressions, from which the actual printing is done, thus releasing a large quantity of type, as well as giving more convenient and permanent plates for the press. When the page has been set up in type, powdered graphite is dusted over it, and a wax composition placed upon it. The wax is then forced on to the type by hydraulic pressure, and on removal constitutes a mould or reverse impression of the type. The wax mould is then powdered with graphite and washed over with a solution of copper sulphate, a few iron filings being sprinkled upon it. This causes a thin film of copper to be deposited chemically upon the graphite, and gives a good conducting surface. The wax mould is now placed in the electrolytic bath, being made the cathode, and a layer of copper deposited upon it. The thickness of the layer depends upon the purpose for which the plate is required, but for ordinary printing, half an hour to an hour suffices for the deposition. On removal from the bath, the thin layer of copper is removed carefully from the wax and then forms a perfect copy of the original type. All that now remains to be done is to fill in the thin copper shell with a backing of type metal, melted and poured in to strengthen the plate, and to plane it down to the right thickness, straightening it if necessary. The plate is then ready for the actual printing press.

There is still another process that may be applied to the electrotype plate, called STEEL-FACING. Owing to the softness of copper, the plate soon wears in the process of printing, the finer parts disappearing first. By depositing a thin layer of iron upon the face of the plate, its life may be greatly extended, and moreover it may be re-faced a

number of times if necessary, so that its life is extended indefinitely. The electrolyte for steel facing is obtained by using a sheet of iron as anode in a saturated solution of ammonium chloride (sal-ammoniac), a thin iron plate being used as cathode. On passage of the current, iron goes into solution at the anode and hydrogen bubbles away at the cathode. When the solution has acquired sufficient iron, the copper plate which is to be "steel-faced" is placed as cathode in place of the thin iron strip. In the course of half an hour a thin layer of iron is deposited upon the plate, giving it the appearance of polished steel. This layer of iron does not in any way spoil the print obtained from the plate, but it is so hard that the number of good impressions obtainable is much greater than from the unprotected copper plate.

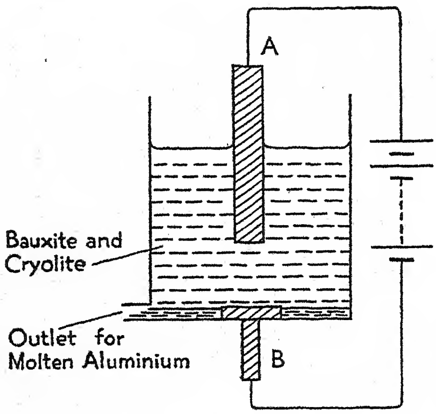


FIG. 81. Preparation of Aluminium.

The preparation of the metal aluminium is another important application of the principle of electrolysis. A mixture of bauxite (a natural aluminium hydroxide) and cryolite (a double fluoride of aluminium and sodium) with a little aluminium is contained in a fireclay receptacle having a carbon anode A, Fig. 81, and a copper cathode B; an arc is struck between the two electrodes which fuses the mixture, rendering it conducting. The electrodes are then separated and molten aluminium forms round the cathode B.

Since the discovery of electrolysis many processes of chemical manufacture have been revolutionised, but their study may appropriately be allocated to the science of

chemistry. The reader who desires to follow them is referred to the volume on chemistry in this series, where the manufacture of substances such as soda, carborundum, and acetylene will be found. It is desirable, however, before closing this chapter to trace the formation and evolution of different types of electric cell or battery from the original Volta type to those of the secondary or storage form, which are now extensively used.

Electric cells may be classed under two heads, PRIMARY CELLS and SECONDARY CELLS. Primary cells are those in which energy in the chemical form is converted directly into energy of electric current, whereas current must be passed through a secondary cell before any current can be derived from it. For this reason the secondary cell is often called a STORAGE CELL or ACCUMULATOR. In the original Volta cell, electrodes of zinc and copper are immersed in, or separated by, a solution of an acid; generally sulphuric acid. As this serves as a type for all cells, we will examine it a little more closely. A rod of ordinary zinc (Fig. 82) when immersed in a solution of sulphuric acid dissolves, forming zinc sulphate, and the hydrogen liberated bubbles away. The equation representing the reaction is—

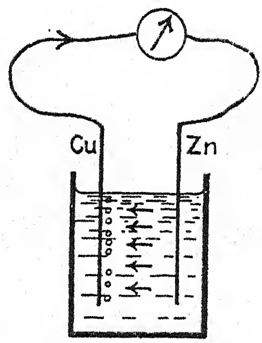


FIG. 82. Simple voltaic cell.

$$Zn + H_2SO_4 = ZnSO_4 + H_2$$

At the same time heat is liberated. The chemical affinity of zinc for SO_4 implies a store of energy, which can be obtained in the form of heat by the above reaction. Of course the hydrogen also has a chemical affinity for SO_4, so that a certain amount of energy is necessary for turning it out of the sulphuric acid, and some of the energy is used in this way. But there is still a balance of energy left which appears as heat. If we now place a copper rod in the

solution, as in Fig. 82, and connect it to the zinc by an external wire, the hydrogen no longer bubbles up from the zinc but appears as bubbles upon the copper instead. At the same time a galvanometer in the external circuit will indicate that a current flows from copper to zinc through the wire, and we conclude, since an electric current only flows in complete circuits, that there is a current from zinc to copper through the cell. It follows that the copper is playing the part of cathode, and from the knowledge we have gained, it will no longer cause surprise that the hydrogen is deposited upon it. On the other hand, the zinc is anode and the SO_4 of the sulphuric acid in solution is deposited upon it, with formation of zinc sulphate ($ZnSO_4$). It is usual to call the copper the positive (+) electrode of the cell, because the current comes by way of it from the cell, while the zinc is called the negative (−) electrode because the current goes through it into the cell. Also, we know that heat is produced in any conductor through which an electric current flows, so that in this simple case the energy liberated when zinc forms zinc sulphate is not produced directly as heat, but as energy of electric current, which becomes heat in the various parts of the circuit through which the current flows. The energy may also take other forms, for if an electromotor be placed in the circuit, some of the energy may be converted into mechanical work, or, in fact, into any of the various forms into which the energy of the electric current can change. It might be thought that the electric cell affords an economical means of producing energy of electric current; and so it would if zinc were sufficiently cheap. But coal is much cheaper than zinc, and it is far more economical to burn coal in a furnace to raise steam, and to drive a dynamo by means of a steam engine, than to burn zinc directly, for that is what it amounts to, in the electric cell. Nevertheless there are some cases where, on account of the small amount of current required, and the reliability of the cell, it is more efficient to use current from a cell than

from a dynamo. Such cases are those of the telephone, electric bell, and the portable flash lamp.

The simple cell of Volta is, however, not very efficient as a producer of electric current. With the arrangement shown in Fig. 82, the current may be fairly strong at first, but rapidly falls off. The cause of this falling off is the hydrogen which collects upon the copper or positive plate, and this for two reasons. One reason is that the hydrogen partially covers up the surface of the plate, and so reduces the effective area for carrying current; and the other is that the hydrogen which, as we have seen, possesses considerable chemical affinity for SO_4, tends to go into solution, and produce a current in the reverse direction to the main current due to the solution of zinc. The hydrogen really forms an electrode, and a cell with electrodes of hydrogen and zinc has a less electromotive force than a cell with electrodes of copper and zinc. It is sometimes said that the hydrogen produces a BACK-ELECTROMOTIVE FORCE, and that under these conditions the cell is POLARISED. Thus the polarisation is objectionable, and many forms of cell have been devised in which the hydrogen is not deposited, or if deposited is quickly removed; for before the development of dynamo-electric machinery, the cell was the only source of current, and the production of an efficient cell or battery, that is, one that would produce a constant current for a considerable time, was a matter of great importance.

Of all the types of cell which have been used, most are now of historic interest only, but there are three kinds which still have important uses. The earliest of these was invented by Daniell in 1836, and is named after him. It has copper and zinc electrodes, but the copper electrode is immersed in a saturated solution of copper sulphate, the zinc dipping into a dilute solution of sulphuric acid. In many forms of Daniell's cell, the copper electrode also forms the outer containing vessel, as in Fig. 83, but the cell is equally efficient if an earthen pot be used, and a piece of copper sheet be immersed in it. The copper sulphate

solution and the acid solution are kept from mixing by means of a pot of unglazed earthenware, or porous pot, through the walls of which the liquids can percolate and so come into contact. The reaction at the negative or zinc electrode has already been explained, and the reaction at the positive or copper electrode may be easily understood, for the copper is cathode, and being situated in a solution of copper sulphate it follows that copper is deposited. Thus no hydrogen is liberated, and the cell does not become polarised, so that its electromotive force remains very nearly constant whatever current is passing through the cell. The value of the electromotive force is about 1·1

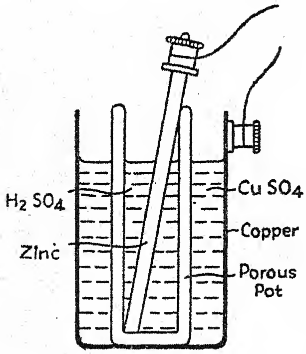


FIG. 83. Daniell's cell.

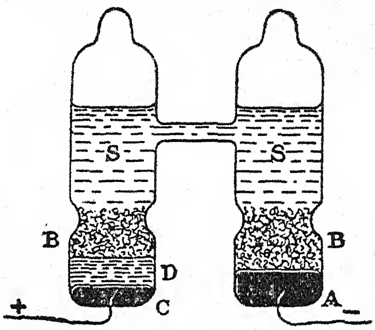


FIG. 84. Cadmium or Weston standard cell.

volt. One point in connection with the behaviour of the Daniell's cell deserves attention; that is, the reaction at the interface of the two liquids. Inside the porous pot there is a drift of SO_4 towards the zinc, and of hydrogen towards the porous pot, and outside, the copper drifts away from the pot and SO_4 towards it. Thus the hydrogen from inside and the SO_4 from outside meet and combine, forming sulphuric acid in the walls of the pot where the two solutions mingle.

The cadmium or Weston cell is of later origin, and its use is due to the great constancy of its electromotive force. It is illustrated in Fig. 84. The positive electrode C is a pool of mercury upon which rests a paste D of

mercurous sulphate. On this rests a paste of cadmium sulphate crystals, and then a saturated solution S of cadmium sulphate. The negative electrode A is an amalgam consisting of 12 parts of mercury to 88 parts of cadmium. When made with carefully prepared pure materials, the electromotive force of the cell is 1·0183 volts at 20° C., and the electromotive force varies very slightly with change of temperature. This cell is accepted as an international standard of electromotive force. It must be used with care, as should any but extremely small currents pass through it, the electromotive force ceases to have the standard value.

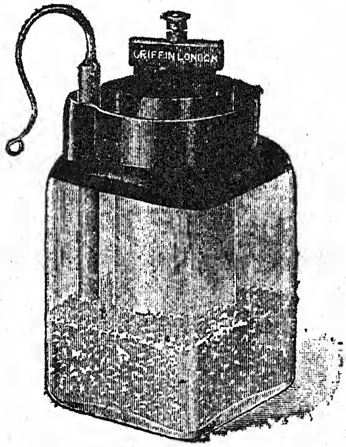


FIG. 85. Leclanché cell.

Of all the primary cells used at the present time, Leclanché's is the commonest. Its peculiar merit lies in the fact that it will give a considerable current for a short time, and although it polarises rapidly, it will recover on being allowed a period of rest. The Leclanché cell is therefore well adapted for telephones and for ringing electric bells, and in fact for any purpose in which an intermittent supply of current is needed. Fig. 85 shows a very common form of the Leclanché cell. The negative electrode is a zinc rod dipping into a strong solution of ammonium chloride (NH_4Cl), commonly called sal-ammoniac. The positive electrode is a plate of gas carbon, and is contained in a porous pot, the space between the carbon and the pot being packed with a mixture of black oxide of manganese (MnO_2) and powdered gas carbon. The solution percolates through the porous pot and the mixture inside, and so reaches the carbon electrode. When current flows, zinc is dissolved, forming zinc chloride,

and ammonia and hydrogen are liberated at the positive electrode, thus—

$$Zn + 2NH_4Cl = ZnCl_2 + 2NH_3 + H_2$$

It is, of course, the hydrogen to which the polarisation is due, but this is slowly removed by the oxygen of the manganese dioxide, and the cell is then ready to produce current again—

$$H_2 + 2MnO_2 = H_2O + Mn_2O_3$$

A very convenient form of the Leclanché cell has come into use, namely, the so-called DRY CELL. Of course no cell can be really dry, that is, without liquid, for there is no known solid electrolyte available. But there is no loose liquid to spill, for the ammonium chloride is made into a paste with sawdust and glycerine, enough water being held in this paste for the working of the cell. It is usual to add some substance such as calcium chloride, which absorbs moisture from the atmosphere, and helps to maintain the cell in a damp condition.

Secondary batteries or accumulators play a very different role to primary batteries, because they can be constructed to give large currents at fairly constant voltage. They are frequently used in conjunction with direct-current dynamos for the supply of current for lighting, or for motors, the battery being charged while the dynamo is running, and supplying the current when it is not convenient to run the dynamo. The first attempt to make a storage battery was due to Sir W. Grove, who made use of the polarisation effect which has already been mentioned (p. 139). He used platinum strips, dipping into dilute sulphuric acid. Each strip is surrounded by a tube containing the solution. On passing a current, hydrogen collects in one tube and oxygen in the other. The platinum strip, surrounded by oxygen, now acts as positive electrode, and that surrounded by hydrogen as negative, and the cell will produce current until the gases have disappeared.

Owing to the smallness of the current which the Grove's storage cell is capable of producing, it did not come into general use. In 1859 Planté used a chemical method of storing the oxygen liberated at the anode. On employing two lead plates immersed in dilute sulphuric acid and passing the current, hydrogen bubbles away at the cathode, but the oxygen at the anode combines with the lead forming lead oxide (PbO_2). On connecting the plates externally, a considerable current can be obtained, the oxidised plate acting as positive electrode. As the current flows, the oxidised plate is reduced, and the negative plate becomes oxidised, until both plates have come to the same state of oxidation. The reactions may be represented thus:

$$\text{(Positive plate) } PbO_2 + H_2 = PbO + H_2O$$
$$\text{(Negative plate) } Pb + O = PbO$$

When both plates have come to the same condition, it is clear that the current will cease, and it is necessary to charge the cell again by a current from some external agency in order to oxidise the positive plate again to PbO_2 and reduce the negative plate to metallic lead. The greater the number of times the cell is charged and discharged, the greater becomes its storage capacity, for the layer of lead produced by reduction of the oxide gets deeper and deeper, and since it is of a spongy form, the electrolyte can penetrate deeper and deeper into the plate. In fact, when the plates are made, the current is passed backwards and forwards through them many times in order to obtain a thick layer of spongy lead. This process is called FORMING the plates, and it adds considerably to the cost of production. The length of the forming process may be reduced slightly by building up the plates from strips of lead burnt at the ends into a framework of lead. A further reduction in the time of forming was made by Faure, who used a lead lattice-work and stamped into the interspaces a paste made of oxides of lead and sulphuric acid. The lead oxide is, of course, reduced on the first passage of the current, so that the time

required for forming is almost eliminated. But Faure, or paste plates, are not so strong as formed plates of the Planté type; they are apt to loosen and flake, and may cause grave injury to the cell. Some makers use Planté formed plates for the positives and paste plates for the negatives, because the positive plates are most subject to deterioration in use.

Lead accumulators are constructed of alternate positive and negative plates, the positives all being connected together by a stout lead strip and the negatives by another strip, as shown in Fig. 86. The positive strip of one cell is bolted to the negative strip of the next, and so on. From

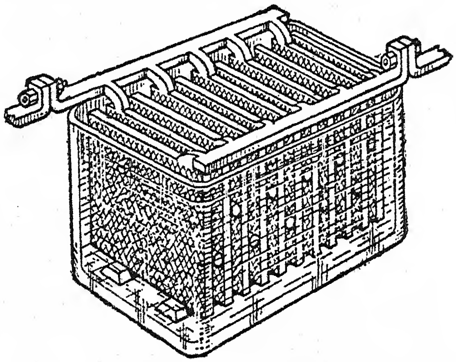


FIG. 86. Secondary or storage cell, or accumulator.

the closeness of the plates to each other and the magnitude of their area, the electrical resistance of the storage cell is very small, and it follows that the current it can produce is considerable. The electromotive force of the lead accumulator is about 2·1 volts, and remains very fairly constant until the cell is nearly discharged. The current at charge and discharge must not be too great, or the plates deteriorate and the cell becomes ruined. A cell with 5 positive plates and 6 negatives will usually stand a current of 40 to 50 amperes, and for a short time even greater currents. For central station work, lead accumulators are used to a great extent, but they require careful and constant attention.

They have also been used for driving electric vehicles, but have not proved a great success. Their great weight is against them, and in the rough usage they experience they rapidly deteriorate.

The next attempt to construct a durable and efficient storage battery was due to Edison. Nickel hydrate packed into nickel tubes carried in a nickel framework constitutes the positive electrode, while finely divided iron oxide contained in pockets in a nickel steel sheet constitutes the negative electrode. Potassium hydrate in solution is the electrolyte. The Edison accumulator has one great advantage over the lead accumulator, in that the mechanical strength of the electrodes enables it to stand rough treatment that would ruin the latter; and it may even be discharged completely, and allowed to remain discharged for a considerable period without suffering seriously, while a similar treatment would probably cause such deterioration of lead plates that they would never recover. This renders the Edison cell particularly serviceable for electric traction and for use in places where the careful attention required for the lead accumulator is unattainable. As set off against this, there is the low voltage of the Edison cell, 1·2 volts, so that for the maintenance of a 100 volts supply, 84 Edison cells would be necessary, while a battery of 50 lead accumulators would suffice.

There is one type of electrolytic action which should be mentioned as it is of considerable service. An aluminium plate immersed in an electrolyte, of which there are many, will only allow current to flow in one direction, that is from the electrolyte to the aluminium plate. The aluminium plate can therefore act as cathode but refuses to act as anode. Using a lead plate for the other electrode interposes no restriction to the flow of current in either direction, so that if one electrode be of aluminium and the other of lead, a cell is obtained which allows the current to flow in one direction only; such an arrangement is really a valve, and it is called the NODON VALVE. Such a valve may be

used to enable accumulators to be charged by means of an alternating current; for on putting the Nodon valve in the circuit, only the half-cycle of current in one direction passes, the other is suppressed. By an arrangment of two or more Nodon valves it is possible to arrange that each half-cycle is employed. The Nodon valve is much less expensive than a motor-generator for converting alternating into continuous current for the charging of accumulators, since the fluctuations of current are of no disadvantage in this case, provided that the current is always in the same direction.

CHAPTER X

Electromagnetic Theory and Wireless Telegraphy

PERHAPS the most difficult branch of science to understand without mathematical knowledge is that which usually goes under the name of "electromagnetics" or "the electromagnetic theory." And yet the foundations were laid more particularly by two men who were not mathematicians, Faraday in England, and Joseph Henry in America, in the early part of the last century. The discovery by Oersted of the magnetic field accompanying an electric current, may be looked upon as the origin of the electromagnetic theory. This was soon followed by the work of Ampère, in which the magnetic fields for all arrangements of current circuit were given in exact and mathematical form. But the phenomena associated with changing currents and magnetic fields were still unravelled. In Chapter III the contribution of Faraday to the electromagnetic theory has been outlined, but it is necessary to consider a little more in detail the advance in knowledge which he made. He was a particularly clear thinker and was not satisfied with any explanation of natural phenomena which was founded upon the doctrine of "action at a distance." Up to Faraday's time, the laws governing the gravitational attraction between bodies, the forces between electric charges and between magnetic poles had been determined with considerable precision, but no one had advanced beyond the position of considering that bodies affect each other when situated at a distance apart. The law of force in these cases is that of the inverse square of the distance. That is, if two bodies, electric charges, or magnetic poles, are situated a certain distance apart and exert a certain force

upon each other, then on doubling their distance apart, the force between them becomes reduced to one-quarter of its previous value. When the distance is increased to three times its original value, the force is reduced to one-ninth, and so on. This law of inverse squares supplies a means of calculating the force under an infinite variety of conditions, but it gives no clue to the reason for the forces. That two bodies between which there is no material communication can influence each other is inconceivable, and this gap in our knowledge led Faraday to consider the space around an electric charge, or a magnetic pole, with close attention. The arrangement taken up by iron filings sprinkled on a piece of paper held near a magnet suggested the idea of lines running from pole to pole, which lines he called magnetic lines of force. A very simple calculation will show that there are lines of force near electrical charges, for on placing a positive charge of electricity at any point, the actual force on it can be calculated, if the position of other charges is known, and the path it would follow is given by the lines of force between a positive and a negative pole in Fig. 87 (*a*) and for two positive poles in Fig. 87 (*b*). To many people these electrical lines of force are merely mathematical lines which serve to map out space in such a way that the force on an isolated positive charge is indicated, just as lines of latitude and longitude are useful mathematical ideas for locating positions and directions. But to Faraday they were something more; they indicated some kind of strain in the medium in which these charges are situated. It is

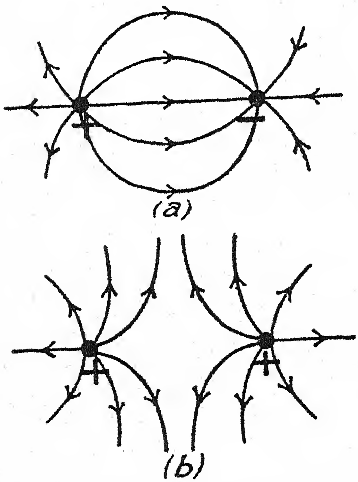


FIG. 87. Electric lines of force due to two charges.

difficult to gain a clear idea of the actuality of the lines of force, but consider for a moment two bodies buried in a slab of india-rubber, and that the bodies are in some way pulled apart. Obviously the india-rubber between the bodies is stretched, and its tendency to recover its original condition pulls the two bodies together; thus the bodies behave as though they attracted each other. Although this idea is very crude, it is helpful in enabling one to realise that the force between two bodies may be due to a state of strain in the medium in which they are imbedded, and the lines in Fig. 87 indicate the directions of the strain. The force between two charges of electricity is just such as would be produced by the lines of force tending to contract. As the lines always arise on a positive and end on a negative charge, the tendency to contract would pull these charges together. But if the lines tend to contract, they would also push each other laterally, so that the repulsion between two charges of a like kind would be accounted for in Fig. 87 (*b*). Faraday was so imbued with the conception of lines of force in the medium that he came to look upon the charge as merely the origin of the lines, and having no physical existence apart from them. This idea is a most fruitful one and placed Faraday far ahead of his contemporaries in many respects.

The great step forward made by Faraday was thus the concentration of our attention upon the medium, rather than upon the electrical charges, and the next great advance was made by James Clerk Maxwell, who represented the conditions of such an electromagnetic field in mathematical form. The comparatively simple equations derived by Maxwell are the expression of two laws, one due to Gauss and the other due to Faraday. Gauss's law relates to the total effect in the space surrounding an electrical charge, or a magnetic pole, and may be rendered into a simple form by saying that a given quantity of charge gives rise to a fixed number of lines of force or, more strictly speaking, lines of induction. The distinction between lines of force

and lines of induction cannot be explained here, but it may be mentioned that in empty space, and approximately in air, there is no distinction between the two. On the other hand, Faraday's law relates to the electromotive force in a circuit when the number of magnetic lines of force threaded through the circuit is changing. It is impossible in a book of this type to give an adequate account of Maxwell's equations; they may be found in works on mathematical electricity, but it should be remembered that, to this day, they are held to give a most complete representation of the effects occurring in an electromagnetic field.

There is no doubt that the most important deduction from Maxwell's equations, made by himself, is that if any change occurs in the state of an electric field, at any place, this change will cause a disturbance which travels outwards in all directions from the place, with a velocity which can be calculated from the electric and magnetic properties of the medium through which it is travelling. Although such motion had not been observed in Maxwell's time (1865), still the measurements made indicated that the velocity should be 300,000 kilometres per second, which is also the velocity that had been measured for light. This suggestive fact made it almost certain that light consisted of waves of electromagnetic change, since the coincidence in the values of the velocities of the two effects was hardly conceivable under any other conditions. What made Maxwell's discovery more significant was the fact that light was known to consist of waves; but there were many theories as to the nature of the medium in which the waves were taking place. For waves consist in motion, and for motion there must be something to move. No known material had mechanical properties such that waves in it would travel with the prodigious velocity of light. And, moreover, light travels best through "empty space" or space free from matter such as we know it, and consequently it was supposed that all space was filled with "æther," which was so light but so rigid that the waves in it had a velocity of

300,000 kilometres per second. Many theories as to the nature of this æther, known as elastic solid theories, were formulated, but each theory encountered great difficulties in accounting for the known properties of waves of light. Most of these difficulties disappear when light is acknowledged to be an electromagnetic wave, which fact alone was of great assistance in furthering the belief in the validity of Maxwell's electromagnetic theory of light. It must not be thought that the phenomena of the electrical field are now thoroughly explained, in the ordinary sense of the term; that is, that the electrical field and its changes, which constitute light, can be accounted for in terms of effects which appeal to our senses. Such an explanation may very well be impossible, because we have no sense which indicates directly to us the presence of electricity. The phenomenon to which we give the name "electricity," is only deduced from our observations of movements produced in ordinary matter; for example, the attraction of light bodies by amber which has been rubbed, by the arrangement of iron filings round a wire, and by the innumerable other movements which have been mentioned in the earlier chapters. But a theory must be judged by its ability, not only to account for observed phenomena, but to predict others, and our belief in what we call electricity led not only to the prediction of the possibility of electromagnetic waves by Maxwell, but also proved the guiding principle which led to the unravelling of the mysteries of X-rays and radioactive changes. Although electricity cannot appeal directly to our senses, there is probably no more deeply seated belief in existence than that which leads us to look upon ordinary material effects as due to the electrical foundations of matter.

In order to understand the later developments of electrical theory we must now turn to a mathematical discussion due to Lord Kelvin (then Professor Wm. Thomson) in 1853, and attempt to explain it without the aid of mathematics. We have seen that a positively charged body attracts a negatively charged body, and we have

explained it by the attraction existing between positive and negative electricity. If now two sheets of metal A and B (Fig. 88) are insulated and A is charged with positive and B with negative electricity, the charges will remain on the plates, since there is no path for their escape. Such an arrangement is called an ELECTRICAL CONDENSER, and if the plates are of considerable extent and are very close together, large quantities of electricity may be accumulated upon them. Although the charges are attracting each other they remain apart, because there is no conducting path along which they can flow in order to combine. But if A and B are connected by a wire, the charges flow along the wire, will combine and so disappear. If the wire connecting them be coiled into the form shown at C, then, while the charges are flowing there is an electric current in C, in fact the motion of the charges is the current, and its direction is shown by the arrows. Now we saw on p. 19 that when there is a current in a coil, there will be a magnetic field, and its form is indicated by the dotted lines of force in Fig. 89. At the moment that the charges are just used up, the current in the coil reaches its greatest strength, and since there is no more charge on the plates, it looks at first sight as though the current must suddenly stop. But there is the magnetic field in existence, and for the current to stop, this magnetic field must disappear. The only way for the magnetic field to disappear is for the magnetic lines of force to collapse, and in so doing they must cut the turns of the coil C, which, as was seen on p. 32, produces an electromotive force in the

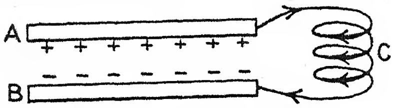


FIG. 88. Charged plates of a condenser connected by a wire.

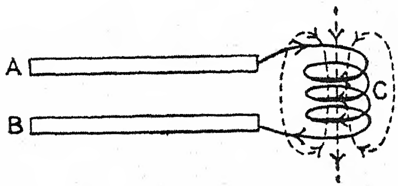


FIG. 89. Conductor at the moment when discharge is complete, but current is flowing in wire connection.

coil. The current therefore continues to flow, which means that positive electricity is still being driven towards the plate B and negative electicity towards the plate A. This goes on as long as there is any magnetic field, and by the time that the magnetic field has disappeared, B has become charged with positive and A with negative electricity. The state of affairs now attained is shown in Fig. 90, and it will be seen that the condition is the same as at the start (Fig. 88) but with the charges reversed in sign. The process now starts again, the charge flowing back and producing a magnetic field in the coil, which continues the current until A is again positively and B negatively charged. The effect of the magnetic field in the coil C is therefore to cause the charges to surge backwards and forwards between the plates, in fact the motion of the electricity is VIBRATORY or OSCILLATORY, just as is the motion of a pendulum. In the act of drawing the bob of the pendulum aside, it is raised to a higher level. On being released it moves to its lowest position and in so doing gains velocity which causes it to mount up on the other side. Thus it continues to swing backwards and forwards. But the swings of a pendulum die away owing to friction and consequent loss of energy, so in a similar manner the electrical oscillations that occur during the discharge of a condenser die away owing to the work done in driving the current through the wire, which is therefore heated.

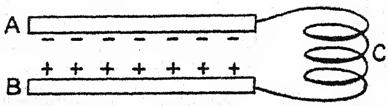


FIG. 90. Condenser or complete reversal of charge.

The oscillatory nature of the discharge of a condenser when the current produces sufficient magnetic field, was foretold on mathematical grounds by Lord Kelvin, but it was not until Fedderson in 1857 thought of examining the spark discharge of a condenser, which had the form of a Leyden jar, by means of a rotating mirror, that the oscillations were actually detected. The jar is charged by means of an electrical machine until the difference of potential

between two metal knobs A and B (Fig. 91) is so great that the air between them becomes conducting for electricity. When this condition is attained, the current passes, with formation of a bright spark. The mirror M forms an optical image of the spark on the screen C. On causing the mirror to rotate, the conducting arm E, carried on the axle D to which the mirror is attached, makes contact between F and G, thus bridging the gap in the condenser circuit at the moment when the mirror is in the proper position to form the image on the screen. If the knobs are far apart, the resistance of the circuit is so great that the discharge

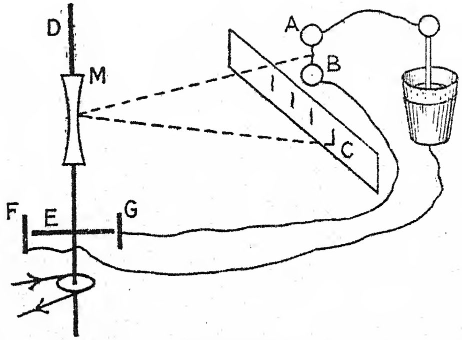


FIG. 91. Apparatus for demonstrating the oscillatory character of the discharge of a condenser.

current does not oscillate, and even at fairly high speeds of the mirror only a single image is formed on the screen at each discharge. But on shortening the gap AB, a condition is reached at which the discharge oscillates, and there is a double image produced on the occasion of each discharge. With shorter gaps five or six oscillations may be produced at each discharge before the spark is quenched. In this way the oscillatory discharge of a condenser, foretold by Lord Kelvin in 1853, was first shown to exist. It is now known that flashes of lightning frequently have an oscillatory character, as may be seen on taking a photograph with a moving camera, a row of several parallel images being produced.

The twenty-three years which elapsed after the publishing of Maxwell's electromagnetic theory in 1865 were not fruitful in the development of electrical knowledge, for it was not until 1888 that H. Hertz detected electromagnetic waves in the space surrounding a conductor in which electric oscillations were occurring. He used many forms of oscillator, one of which is shown in Fig. 92, in which the conductor AC, consisting of two attached knobs, is joined to one pole of an induction coil, and BD to the other pole. On causing a spark between A and B, electromagnetic waves travel outwards from the oscillator. Hertz's particular discovery consists in the detection of these waves.

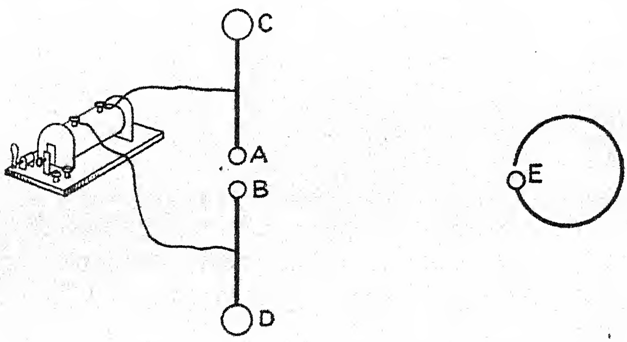


FIG. 92. Hertz's arrangement of oscillator and detector.

A ring of metal with a minute gap at E is affected by the waves; for every time a spark occurs at AB, a minute spark is seen at E, even when E is fifty or sixty feet away from AB. This discovery was a great step forward, in fact it was the one condition required to establish the electromagnetic character of light and to open up the way to electric signalling without wires. It should not be forgotten that at about this time Sir Oliver Lodge showed that the discharges of a Leyden jar could produce discharges in a neighbouring Leyden jar of the same size, if a small gap was left in the wire connecting the coatings of the second jar. Thus Lodge discovered independently the fact that

the electromagnetic waves are emitted by a Leyden jar discharging between knobs, and could produce similar oscillations in a suitable conductor upon which the waves fall. But Lodge did not give the conditions of the phenomenon nearly so completely as did Hertz. It was shown by Hertz that the waves could be concentrated into a beam by placing a curved metallic mirror behind the oscillator, as can a beam of light by means of a suitable reflector. Also the wave-like nature of the radiation from the oscillator was clearly demonstrated; and the length of the waves was found to be about five metres, whereas the wave-length of light waves is about 0·00006 centimetre. Other experimenters soon showed that the waves could be bent on passing from one substance to another, in fact that they had all the properties of waves of light, including their prodigious velocity of 300,000,000 metres per second.

Before proceeding to the modern application of the Hertzian waves it is necessary to gain a clearer idea of their nature. There are several ways of representing them, the most powerful of which is, of course, that of mathematical analysis; but the use of Faraday's idea of lines of force has proved of such great help that many writers speak of the waves in terms of lines of force. One difficulty should be mentioned at the start: lines cannot completely fill space, so that gaps will be left between them, and it seems as though the effect of one line upon another must be excited across this empty space. The difficulty is removed by considering the mapping out of space to take place by means of TUBES OF FORCE which actually touch each other and so fill the whole of space, leaving no gaps, in a manner somewhat similar to the cells in a honeycomb. Instead of drawing the tubes, it is convenient to draw a line down the axis of each tube to represent it. The whole convention is one of convenience in considering the effects around electric charges, and it is of no consequence what convention is adopted, provided that it enables us to follow the electrical conditions occurring in electrical fields. With

this explanation, we shall now decide on employing electrical lines of force in our discussion.

Consider two wires ending in knobs A and B in Fig. 93 (i). If the upper rod is charged with negative electricity and the lower rod with positive electricity, the lines of force are as shown and are at rest. For the sake of clearness, only the lines on one side are shown; in reality the whole space round the conductors is filled with lines. If now the air gap between A and B suddenly becomes conducting for electricity, the lines of force begin to contract, because the positive and negative charges can flow together across the conducting bridge, and it will be seen that every part of each line is travelling towards the gap, and is moving

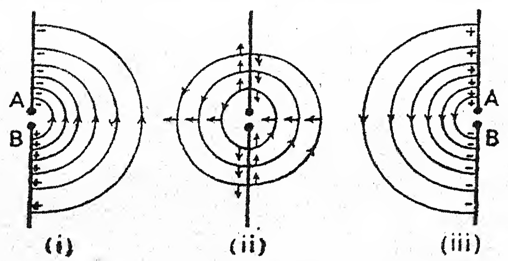


FIG. 93. Electric lines of force surrounding an oscillator.

perpendicularly to itself. At the same time, the motion of the positive charge upwards and the negative charge downwards is really an electric current flowing upwards through the conductors, and a current such as this is surrounded by a magnetic field, of the form shown in Fig. 5, p. 14. Hence we conclude that electric lines of force in motion constitute a magnetic field, and the direction of the magnetic field is at right angles to the electric lines of force and to their direction of motion. The three effects are related to each other like the three sides of a cube, as shown in Fig. 94. This conception of a magnetic field, as the motion of an electric field at right angles to itself, has been developed by Sir Joseph J. Thomson, and has been of great service in the representation of electromagnetic waves. It supplies the

one property of the electric lines of force which was wanting in Faraday's original idea, namely, momentum when in motion. Momentum is a property of ordinary matter in motion, which prevents the motion being increased or decreased suddenly. It is the momentum of the pendulum at the lowest point of its swing that carries it past this point and causes it to mount up on the other side. So the lines of force as seen in Fig. 93 (ii) have momentum which carries them through the gap so that they spread out on the other side until their tendency to contract brings them again to rest, as in Fig. 93 (iii). In (ii) they are just half-way; the electric current is at its greatest value, and the position of the electric lines of force shows that the charge is at this instant zero; but the lines are in motion and their momentum will carry them on until condition (iii) is reached, when it will be seen that the charges are exactly reversed from their original condition (i). If the air gap is still conducting, the process now starts again in the reverse direction, and after another similar oscillation the state of (i) is reached again. This oscillatory process is identical with that occurring in the oscillatory discharge of a condenser, worked out by Lord Kelvin (p. 151), but it has been explained from a different point of view, which is more suitable for following the radiation which occurs in wireless telegraphy.

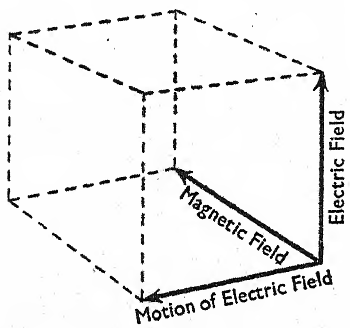


FIG. 94. Relation between the directions of magnetic and electric fields in an electric wave.

The conductors of Fig. 93 correspond to the Hertz oscillator, but it is not yet evident why radiations should occur. In order to follow the process of radiation, consider Fig. 95 (i), in which the more distant lines of force are shown, although only half the complete diagram is given, as

in the previous case, for the prevention of confusion. The shorter lines such as ABC, EFG, will pass through the air gap as before, but the ends L and N of the more distant lines will arrive at the gap before the more distant part M. Remember that every line has momentum which carries it onwards, always in a direction at right angles to the line itself, and it will be seen that the shape of the line LMN will become LKMKN, as seen in Fig. 95 (ii). Now this, for reasons which cannot here be given, is an unstable condition, and the line breaks into a loop PM, and a short line NKL seen in Fig. 95 (iii), and the loop PM is pushed outwards by the neighbouring lines. Once in motion, it continues so by virtue of its momentum. A more complete representation of the formation of the electric lines of force

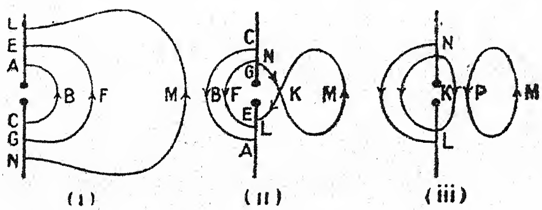


FIG. 95. Electric lines of force forming radiation loops.

given out from a Hertz oscillator is given in Fig. 96, where eight stages of one half-oscillation are shown. It will be seen that between *a* and *c* (Fig. 96 (viii)) the direction of the electric field is downwards, and from *c* to *d* it is upwards.

By means of the Hertz oscillator, waves can be produced which he detected over distances up to 50 or 60 feet, and there is no doubt that with the sensitive detectors now in use these waves might be detected over many times that distance. But really long-distance transmission was rendered possible by the use of greatly extended oscillators by Sigr. G. Marconi in 1898, who employed a mast or vertical wire, called an AERIAL, as an oscillator, the spark taking place between knobs as before, but one attached to the aerial and the other to the ground. It is thus clear that only

half the diagram of Fig. 96 is applicable to this case, and the form of the lines of force will be more as shown in Fig. 97. The diagram is not drawn to scale; the upper layer of the atmosphere FG, which is more conducting than the rest, is

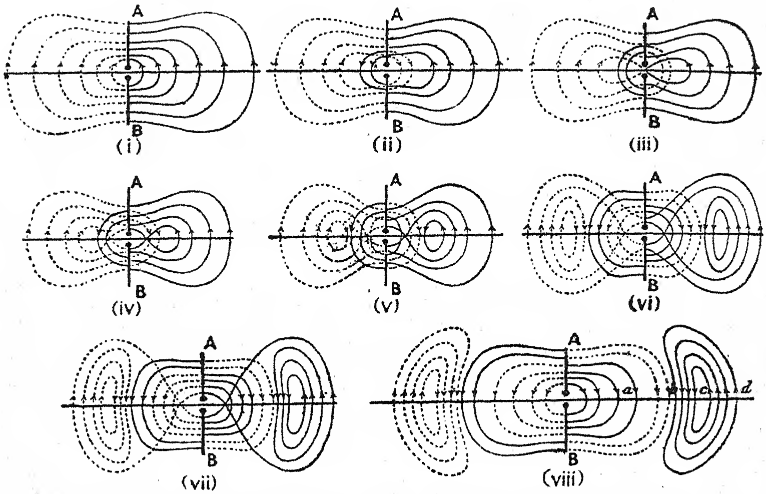


FIG. 96. Electric lines of force near an oscillator during radiation.

shown, and should be at a much greater elevation than is indicated. Nevertheless, the diagram shows the loops travelling outwards, the field at *a*, *c*, and *e*, etc., being in one direction and at the intervening positions *b*, *d*, etc., in

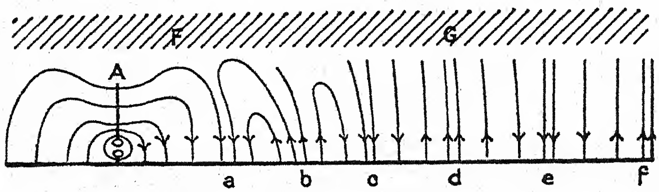


FIG. 97. Electromagnetic waves proceeding outwards from an aerial.

the reverse direction. At a distance from the aerial A the waves are nearly vertical, and are of course travelling outwards with the velocity of light, 300,000,000 metres per second. The frequency of oscillation commonly used in

wireless telegraphy varies from 24,000 to 30,000,000 oscillations per second, which shows that the length of wave varies between $\frac{300000000}{24000}=12,500$ metres and $\frac{300000000}{30000000}=10$ metres. Accompanying the electrical lines of force there will be, of course, magnetic lines of force at right angles to the electric lines and to the direction of travel of the waves. The magnetic lines are most closely crowded together at *a*, *b*, *c*, etc. (Fig. 97), and the magnetic field is zero between them. Also the magnetic lines of force travel with the same speed as the electric lines. The magnetic lines of force cannot be shown conveniently in the same diagram as the electric lines, being at right angles to them, and they are consequently left out of the figure. Generally we shall omit mention of them, but it must be always borne in mind that whenever the electric lines are travelling, they are always accompanied by the magnetic lines. The very condition of motion of the electric lines is that there should always be magnetic lines at right angles to them, and the velocity of motion in the empty space (or in air) is then 300,000 kilometres per second, or the velocity of light.

It is interesting to review the electromagnetic radiations with which we are acquainted, and to realise how they form a long series, from the lowest frequency to the highest. In the case of sound or air waves, the lowest note that the ear can detect has a frequency of about 10 oscillations per second and the highest about 25,000 per second, comprising in all just over 11 octaves. But when we turn to electromagnetic waves we find a vastly greater range, although, of course, the eye is only sensitive to the waves comprising a very small portion of this range, extending over about one "octave," to borrow an expression from music. Nevertheless, the visual rays are of by far the greatest importance, and the study of them has given us the key to the whole sequence. It was Sir Isaac Newton who first examined white light and showed it to be a mixture of different rays, by passing it through a glass prism. The prism bends the differently coloured rays to

different extents and so separates them. The appearance of the spectrum of white light is well known, the arrangement of colours being the same as that in the rainbow. The extreme red rays are bent least by the prism, and have a wave-length of about 0·0001 of a centimetre, while the extreme violet rays are bent most and have a wave-length of about 0·00005 of a centimetre. Between these the various colours, orange, yellow, green, and blue, are ranged. Photography has revealed the presence of other rays beyond the violet, to which the eye is not sensitive, called the ultra-violet, or actinic rays, and the study of heat has proved the existence of still other rays beyond the red, the infra-red rays whose heating effect alone can be detected. But far beyond the infra-red, the ordinary electromagnetic waves come into the series, and beyond the ultra-violet are the X-rays and γ-rays. The diagram of Fig. 98 makes an attempt to draw the spectrum as it would be if all the known electromagnetic rays could be arranged side by side as in the ordinary light spectrum. Of course the range of wave-length is so great that one single diagram drawn to true scale could not give them all; their true positions are only indicated by the values of their wave-lengths. The whole range comprises about 60 octaves and all these waves have been detected, and in many cases used for important purposes. It is a significant fact that one of the

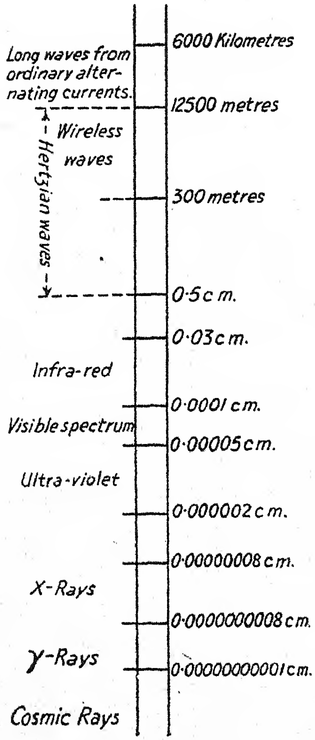


FIG. 98. Diagram showing the various electromagnetic waves.

most sensitive detectors, if not the most sensitive, is the eye itself, and that of all the rays emitted by the sun and constituting ordinary sunlight, the greatest intensity of the rays occurs for just those rays to which the eye is sensitive. Thus the eye has been developed to make use of the rays which the sun emits most copiously.

The earliest method of producing electromagnetic waves for the purposes of wireless telegraphy consisted in causing sparks between knobs, by means of an induction coil, as in Fig. 92. This method has, however, many disadvantages and has been replaced by several others, of which the next type in order of development is shown in

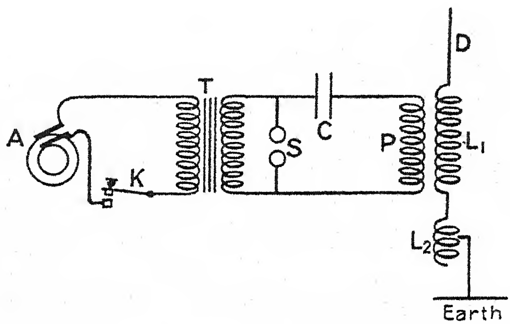


FIG. 99. Method of exciting oscillations in an aerial.

Fig. 99, which represents a type used for many years. An alternating-current dynamo A and transformer T produce a sufficiently high electromotive force to produce sparking at the knobs S whenever the key K is depressed. An induction coil may be used in place of the alternator and transformer when only small power is to be transmitted; but for long-distance telegraphy, when considerable horsepower is required, the alternator is essential. At each spark, electric oscillations are set up in the circuit SCP, containing the condenser C, and coil P. A second coil L_1 is wound upon P, or is very close to it, so that P and L_1 act as a transformer, the oscillatory current in P causing an oscillatory electromotive force in L_1. L_1 is in series with

the aerial or antenna D, so that oscillating currents are produced in this, which currents give rise to the radiated waves just as in the conductor A in Fig. 97. The lower end of the coil L_1 is connected to earth through another coil L_2 which has a movable contact, so that a part or the whole of L_2 can be included in the aerial circuit. The advantage of this method of production of waves is that by varying the amount of L_2 included in the aerial circuit, and by varying the capacity C, the two circuits DL_1L_2, and SCP may be *tuned* to each other, that is, the natural frequency of the oscillations in the two may be made the same. When this tuning is effected, the oscillations in the aerial are much more powerful than would otherwise be the case. This process of tuning may best be understood by considering a corresponding case in the production of sound waves. If a whistle or tuning-fork be held near the mouth of a hollow vessel, or organ pipe, the air in the pipe will be set in violent vibrations and will "speak" when the natural frequency of vibration, or "pitch," of the whistle or tuning-fork is the same as that of the organ pipe. But when the tuning is not perfect, the pipe is silent. There is another advantage in tuning to a suitable frequency in the case of wireless, for the waves emitted by different stations may be given different frequencies, so that at the receiving station the receiving apparatus may be similarly tuned, and the waves from only one transmitting station at a time will affect the instruments, such tuning being termed SYNTONY. The confusion that would arise when many stations are emitting waves, if all these waves affected all the receiving stations, may be imagined.

The oscillations and waves produced in the manner just described are heavily *damped*, that is, they die out after a few oscillations. Such an oscillation may be represented in a diagram as in Fig. 100. Thus, the curve ABCDE represents a heavily damped oscillation, and it will be understood that after the point C is reached the current is so small that it is ineffective in producing radiation. The

curve AFGH represents an oscillation which is undamped, and we shall see later how such oscillations may be produced. A common frequency of oscillation occurring in wireless practice is about 100,000 per second, and if the damping is so great that after 10 oscillations there is no radiation, then after a lapse of $\frac{1}{10000}$ second the radiation has ceased, and will not start again until the next spark occurs. There may be 500 sparks per second, which would mean that in the whole of one second, radiation is only going on for $500 \times \frac{1}{10000}$, that is $\frac{1}{20}$ of a second, owing to the comparatively long intervals between successive sparks. This means that the radiation can never, under these

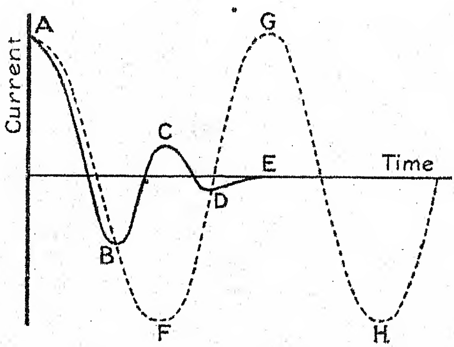


FIG. 100. Damped and undamped oscillations.

conditions, be very efficient, since for only $\frac{1}{20}$ of the time is radiation going on. There have been many methods devised for obtaining continuous radiations, and since these require undamped oscillations, the production of continuous or undamped oscillations is an important problem. This has been finally solved by the use of the triode valve, which is dealt with later in this Chapter.

The development of wireless telegraphy has been rendered possible on account of the discovery of sensitive methods of detecting electrical oscillations. The first detectors were merely circuits, in some cases similar to the oscillating circuit, in which the waves falling upon them set up

oscillatory currents of sufficient strength to cause a minute spark at a gap in the circuit. The tuned Leyden jar of Lodge, and the loop of wire of Hertz (E, Fig. 92), are of this type. Professor A. Righi used a series of resonators consisting of thin strips of silver, made by scratching the silver from a silver plate-glass mirror, the required strips being left on the glass. They are made of various lengths, and each strip has a gap at its middle, AB (Fig. 101). When the waves have the same frequency as the natural frequency of any one strip, oscillatory currents are set up in the strip, and a minute spark can be seen at the gap. The effect is similar to that which occurs when electromagnetic waves fall on an aerial, although, of course, much more sensitive detectors than a mere spark gap are now used. If the waves are represented by their electric lines of force CDEF (Fig. 102) travelling from left to right towards a resonator AB; while the part of the field represented by E is passing AB, there is an electric field

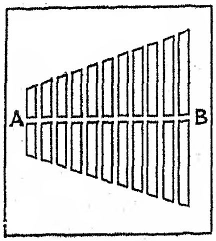


FIG. 101. Righi wave-detector.

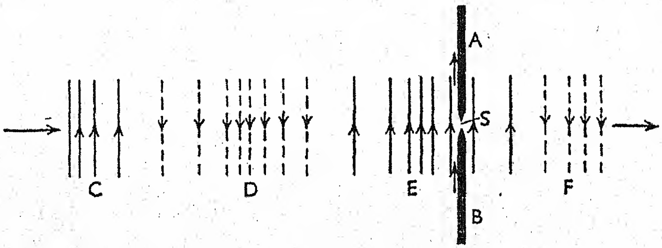


FIG. 102. Electromagnetic waves producing oscillation in a detector.

directed upwards and a current will be caused to flow upwards in the conductors AB. Similarly, when D or F is passing, the field and current will be downwards; and if the natural period of oscillation for the circuit AB is the same as that of the oncoming waves, each wave, as it arrives, tends to strengthen the current in A and B. It follows that

after a few waves have passed, the surging of electric charge up and down AB may be sufficiently violent for the gap S to be jumped, with formation of a spark. This tuning, or resonance, is an important factor in sensitive receiving in wireless.

A very important step in the detection of electromagnetic waves was made by E. Branly in 1890. He used a property of metallic contacts, which had been known for some time, but is not even now understood completely. When electric waves fall upon a loose mass of metallic filings the electric resistance of the mass falls considerably, but is rapidly restored to its original amount by mechanical disturbance such as tapping. Such an arrangement was named COHERER by Sir Oliver Lodge, and the name has come into general use. One form of Branly coherer is shown in Fig. 103 (*a*), in which a quantity of iron filings A, contained in a glass tube B, can be slightly compressed by two metallic plugs C and D, which also act as terminals. On connecting a battery to C and D, with a detector or galvanometer in the circuit, it is found that when electric waves from the discharge of a Leyden jar through a coil of wire fall upon the coherer, the current is increased to a considerable extent owing to the drop in electrical resistance of the mass of iron filings. A slight tap to the tube will restore the current to its original value. Many metals were used, the best effect being obtained with those which are moderately oxidisable, such as iron, nickel, and silver. Marconi, in 1896, brought the coherer to its most efficient form by using a mixture of nickel and silver filings between silver plugs. The filings A are placed between the tips of two silver plugs B and C (Fig. 103 (*b*)), contained in a glass

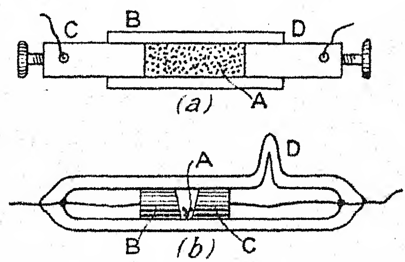


FIG. 103. Coherers.

tube which is exhausted of air and sealed at D. The coherer is placed in the aerial circuit, and the small oscillatory currents in it cause a drop in electric resistance of the filings sufficiently to enable the current from a cell through it to close a relay (p. 95); a stronger local current then actuates an inking recorder (p. 97). At the same time the relay, or in some cases the tapper of an electric bell, is allowed to strike the coherer and so restore it to its original condition. It is then ready to receive the next signal.

Amongst the further developments in receiving apparatus, the magnetic detector is of special importance, owing to the wide use to which it was put. The effect of the current from a discharging Leyden jar upon steel needles had for a long time been puzzling, and different workers had failed to find any constant effect. Sometimes the steel was magnetised in one direction, sometimes in the other, and sometimes it was not magnetised at all. To Sir Ernest Rutherford is due the credit of making an important discovery. A piece of steel, situated inside a solenoid, and magnetised to saturation, is found to be only partially magnetised after a rapidly oscillating current has been passed through the solenoid. Rutherford showed that in this way electromagnetic waves producing an oscillatory current in the solenoid caused a reduction in the magnetisation of a steel wire. This arrangement was modified by G. Marconi, who devised a continuously-acting wave detector, which depended for its action upon the effect of rapid electric oscillations upon magnetisation. A continuous cable of silk-covered iron wire AB (Fig. 104) passes over two pulleys C and D, which are in rotation, so that the wire between A and B passes under the four poles S, N, N, S of two horse-shoe magnets. Thus the wire is strongly magnetised in one direction as it passes under the first pair of poles, and in the reverse direction as it passes under the second pair. Whilst in these fields the iron wire passes through a solenoid EF, through which the current produced

in the aerial by the electromagnetic waves is passing. The exact effect of the oscillations upon the magnetisation is still open to some doubt, but it is certain that it produces an alteration in the magnetic conditions of the wire, and that this alteration, whatever its character, produces induced currents in the coil G wound over the central part of the solenoid. This, in turn, produces current in the telephone receiver T, and a sound will be heard on placing the receiver to the ear. Thus on the arrival of each train of waves at the aerial, a click will be heard in the telephone receiver, and on the stoppage of the waves, the horse-shoe magnets will restore the original magnetic condition of the

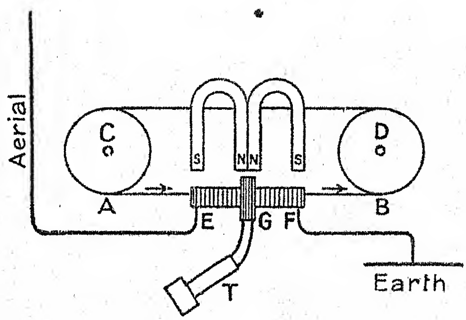


FIG. 104. Marconi magnetic detector.

iron wire, and another click will be heard. Owing to the great sensitiveness of the telephone, comparatively feeble oscillations can be detected in this way, and the passage of each train of waves produced by each discharge or spark at the sending station causes a sound in the telephone, which sounds build up into a continuous hum, interrupted or started by the opening or closing of the Morse key in the actuating circuit. By means of the Morse key, long and short sounds may be produced in the telephone, corresponding to the dashes and dots of the Morse code. The telephone cannot, under any circumstances, be affected directly by the oscillations in the aerial circuit produced by the electromagnetic waves, the frequency of which varies

between 2×10^4 and 3×10^1 per second. The greatest frequency which the ear can detect is about 25,000 per second, but this is a very shrill note, and is beyond the limits of hearing of many people. Another and much lower limit in frequency imposed by the use of the telephone is due to the fact that the diaphragm of the receiver itself cannot be caused to vibrate very rapidly. The frequency of vibration employed in ordinary speech lies chiefly between 500 and 1000 vibrations per second, the latter being a fairly high pitch. It is thus clear that the rapid oscillations used in wireless transmission cannot cause the diaphragm to vibrate, and even if they could, in the higher frequencies the ear would be incapable of detecting such vibrations.

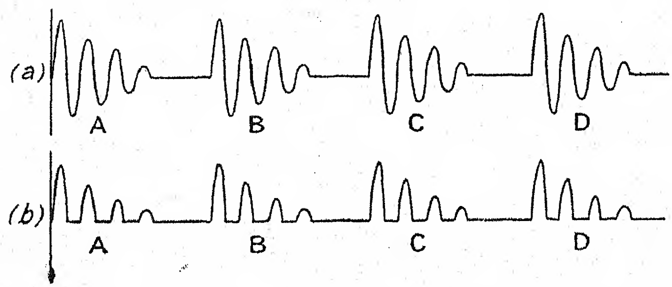


FIG. 105. "Rectification" of waves.

Nevertheless the direct effect upon the telephone of the waves has been largely employed for the receiving of wireless signals. Consider the wave trains A, B, C, and D (Fig. 105 (*a*)). The separate oscillations of each train are, as we have just seen, far too rapid to affect the telephone. But suppose that the lower halves of all the waves could be suppressed, then we should have the state of affairs shown in Fig. 105 (*b*). The upper halves of the waves A follow each other so rapidly that their effects upon the diaphragm of the telephone, being all in the same directions, are added together, and the wave train A gives one impulse upon the diaphragm and results in a single impulse being heard. Similarly for B, C, D, etc., and if these impulses succeed

each other sufficiently rapidly they build up into a continuous note of definite pitch when the receiver is applied to the ear. The frequency of this note is the number of trains of waves A, B, C, D, etc., arriving at the aerial in a second, and not that of the separate waves in one train. The frequency of the trains of waves is fixed by the rapidity of the make and break of the sending current circuit.

Several systems have been devised to make use of the heating effect of the oscillatory current as it passes through a very fine wire for the purpose of reception, but the extreme sensitiveness of the telephone, and the readiness with which signals in the telephone are adapted to the Morse code has resulted in the neglect of other methods of reception.

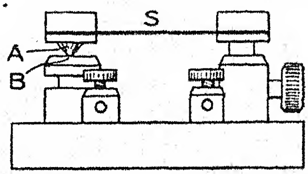


FIG. 106. Crystal detector.

Many successful attempts have been made for the suppression of one-half of the oscillations, or as it is sometimes called RECTIFICATION, to enable the electric waves to be detected by the telephone. This method requires some form of valve, or RECTIFIER, which will allow current to pass in one direction only, or at any rate, to pass more freely in one direction than in the other. The CRYSTAL DETECTOR employed is a rectifier of this type. It usually consists of a crystal of some kind pressing against a metallic surface, the most common type being a crystal of carborundum pressing against a surface of steel, or in the most modern form, a tungsten wire touching a surface of a crystal of germanium. The crystal A (Fig. 106) is fixed in a mass of solder or fusible metal, and is maintained in contact with the metal surface B by the flat spring S. A small electromotive force tending to drive an electric current across the point of contact of the crystal and metal will produce a current whose value depends upon the direction in which the electromotive force acts, so that an oscillatory electromotive force such as is produced when

electromagnetic waves fall upon the aerial, will produce more current when directed one way across the crystal contact than in the reverse direction. Thus the halves of the waves (Fig. 105) are not completely suppressed, but more current flows in one direction than in the other, so that there will be a resultant current remaining in one direction which will affect the receiving telephone. In Fig. 107 a curve is drawn showing the character of the relation between electromotive force and current in the case of a carborundum-steel detector. For an alternation of electromotive force between two such points as A and B, the amount of rectification is very small, but if the mean value of the electromotive force be OH, instead of zero, a current corresponding to DF will flow at the extreme value of one half-cycle, and current CK for the other. Thus the current in the telephone will oscillate about GE, being EF for one extreme and GL for the other, and the resultant current will be proportional to the difference between these two. Hence the more sharply the curve bends upwards, the more effective will be the rectification. For this reason an auxiliary battery B (Fig. 108) is employed which maintains a current in a resistance R, provided with a movable contact, so that the average electromotive force acting across the crystal contact can be varied until the best condition for rectification is found.

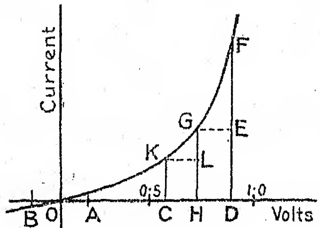


FIG. 107. Diagram explaining "rectification" by a crystal detector.

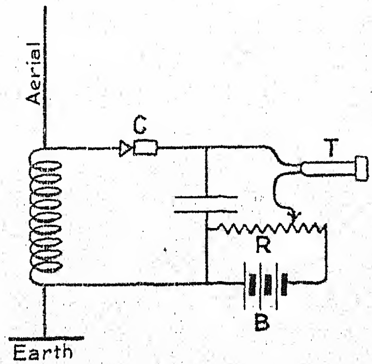


FIG. 108. Receiving by means of a crystal detector.

This is appreciated by the signals then being heard most loudly in the telephone T.

An alternative to the crystal detector is the thermionic valve of Prof. J. A. Fleming (1904), which makes use of an earlier discovery of Edison, that in a highly exhausted incandescent lamp an electric current will flow from a third conductor to the filament, but not in the reverse direction. One arrangement for the receiving of wireless signals, as given by Prof. Fleming, is shown in Fig. 109. The battery B maintains the filament F of the glow lamp, either carbon or tungsten, in incandescence, while the adjustable resistance R_1 can be varied until the proper temperature of the filament is attained. The hot filament emits quantities of electrons, or negative charges of electricity (see Chapter XI), and if F is at a higher potential than P these electrons cling to the filament, but when P is at a higher potential than F they are driven from F to P, being negative charges, and a considerable electric current flows from P to F. It should be remembered that a positive electric current is in the direction of motion of positive electric charge, and in the opposite direction to the motion of negative charge. Thus the valve acts as a rectifier, so that the electric oscillations in the aerial and primary coil P_1, produce similar oscillations in the secondary coil S, which are rectified by the valve FP, and so produce sounds in the telephone T. Thus the valve has a similar rectifying effect to the crystal detector.

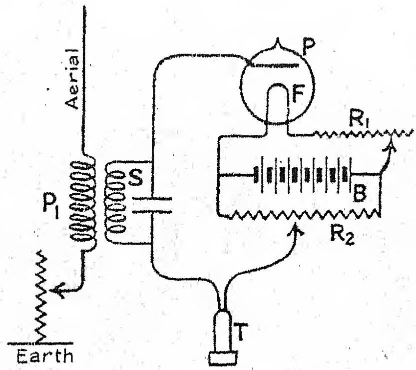


FIG. 109. Receiving by means of the Fleming rectifying valve.

One of the greatest strides made in radio-telegraphy is due to the addition by L. de Forest, in 1907, of a third

electrode or grid to the Fleming valve, thus converting it into an instrument of far-reaching utility, which has received many names. The name most commonly used is "triode" (three electrodes), although it may also be given other names, e.g. audion, rectifying valve, amplifying valve, according to its particular use. The triode has many forms, but they all contain the three parts, a hot filament F, metallic gauze or grid G, and metallic plate P, shown in Fig. 110. The filament is maintained in a state of incandescence by the current from a battery B, consisting

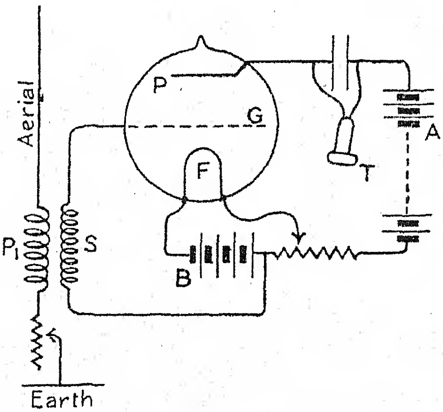


FIG. 110. Receiving by means of the triode.

of a few secondary cells, and thus emits quantities of electrons into the space immediately surrounding it. If an electromotive force acts from the filament F to the grid G, the electrons liberated are driven back to F (remembering that they are negative charges), so that no current can pass out from F because, the bulb being exhausted to the highest possible vacuum, the only carriers of current are the electrons emitted by the hot filament. Thus, whether or not there is an electromotive force acting from the plate P to the filament F, there are no carriers of electricity near P, and the battery A of many cells cannot produce any current. On the other hand, if an electromotive force acts

from the grid G to the filament F, electrons stream away from F, and many of them pass through the grid and arrive at P. The battery A is now able to produce considerable current in the direction of P to F, in fact, owing to its greater electromotive force, it produces a much greater current than that flowing from G to F. Thus a small variation in electromotive force, acting between the grid and the filament, produces much larger variations in the current from the plate to the filament, than in the current from the grid to the filament. In Fig. 111 this is illustrated, although the diagram is not drawn to scale. A small oscillating electromotive force acting from grid to filament, whose mean value is O*e*, and extremes O*f* and O*g*, will produce currents from plate to filament, represented by *fb* and *fc*, which are much greater than the current from the grid to the filament. This magnifying or amplifying effect of the triode renders it of the greatest importance in all cases in which small variations in electromotive force

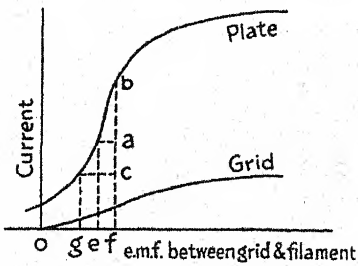


FIG 111. Diagram showing the amplifying effect of the triode.

or current are to be detected, for it gives a means of magnification of these small oscillations, which could not be detected by the telephone, into larger ones which produce a readily audible effect. In Fig. 110 the coil P_1 in the aerial circuit acts as primary to the secondary coil S, which is in the grid circuit, and the minute oscillations, being magnified by the triode, produce audible effects in the telephones T. The triode also acts as a rectifier, for if O*e* (Fig. 111) represents the average electromotive force acting from the grid to the filament, due to its connection with the positive end of the battery B, and *eg* and *ef* represent the extreme variations in the electromotive force due to the oscillation produced by the incoming electromagnetic

waves, the current in the plate circuit varies between *fb* and *fc*, and the increase *ab* for one half-cycle is greater than the decrease *ac* for the other half. Thus rectification occurs exactly as in the case of the simple rectifying valve or the crystal detector. This is due to the upward bend of the plate current curve, and the greatest rectifying effect is produced by working at that electromotive force between grid and filament at which the plate current curve bends up most sharply. A small incoming current may be multiplied up many times by such a device, or putting it another way, the signals will be of the original strength when employing only a fraction of the original power. Hence much greater distances are now possible for the employment of wireless telegraphy, while for moderate distances much smaller aerials can be used, both for sending and receiving, than could be employed before the advent of the triode.

Still greater magnifications can be attained by using triodes IN CASCADE, that is, by using the large variations in current in the plate circuit to produce still greater variations of current in the plate circuit of another triode, whose variations in the plate current are thus a second magnification of the original signals. One method of connecting two triodes in cascade is shown in Fig. 112, in which the small battery heats both filaments, and the large battery is connected to both plates, while the plate P_1 is connected to the second grid G_2, the telephones being in the circuit of the second plate P_2. With the development of radio, valves and amplifying circuits have been greatly improved and many modifications of the simple form shown in Fig. 112 have been introduced. Amplifications of a million times are readily obtainable and are applied in radio and in trans-Altantic and other telephone transmissions.

Another extremely important use to which the triode may be put is the generation of oscillatory currents of the undamped form. For it is clear that if oscillations set up

in any way in the plate circuit can, by the employment of part of their energy, be made to produce suitable oscillations in the grid circuit, these latter, by their reaction on the plate current, increase its variations, or at any rate

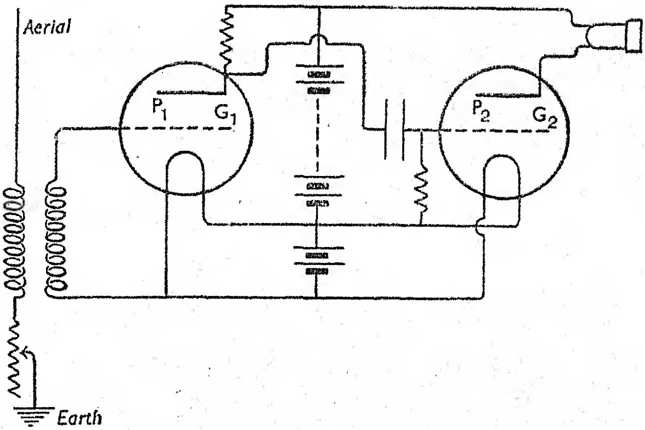


FIG. 112. Multiplying effect of two triodes in cascade.

make good the loss which occurs by radiation. Thus in Fig. 113, the grid and plate cicuits may be coupled together by the transformer L_1L, so that oscillations in current in L will induce oscillating electromotive forces in L_1, which if properly connected to the grid G, will have the effect of reinforcing the original oscillations. The effect is somewhat similar to that of a reed in the blowing of an organ pipe, which in being opened and shut by the vibrating column of air in the pipe, allows air to be blown into the pipe at just the correct instants to increase the vibration.

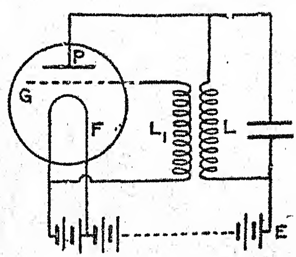


FIG. 113. Triode used as a generator of oscillations.

One of the greatest marvels of the present day is the transmission of speech or music by wireless means. The condition necessary for success is the production of a

microphone which will modify the intensity of the waves emitted by the aerial in a manner similar to that in which the carbon microphone modifies the current from a battery in ordinary telephony (p. 112). Many liquid microphones were tried, whereby the current from the generator (alternator, or electric arc) passed through the liquid, whose resistance was varied by means of the movements of the diaphragm, upon which sound waves fell. The results were only partially successful, and this method has now been replaced

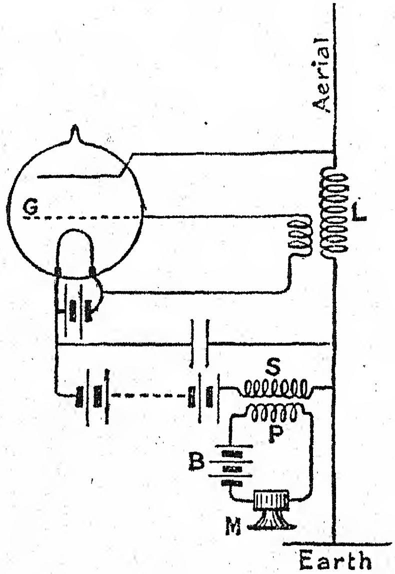


FIG. 114. Employment of the triode in wireless telephony.

by the employment of the triode. For if the current in the plate circuit of the triode, used as a generator, can be modified by a carbon microphone, so that the fluctuation in intensity follows the motion of the diaphragm of the microphone, the telephones at the receiving station are affected in a similar manner. Instead of the abrupt starting and stopping of the waves produced by a Morse key, which are heard as clicks in the receiving telephone, fluctuations in intensity are produced, following each other at the same

rate as the modification in current produced by the motion of the diaphragm of the microphone at the sending station. There are many methods of bringing this about, and some of them are of great complexity; but a simple method is illustrated in Fig. 114. The microphone M produces fluctuations in the current in the circuit PBM, and the secondary coil S of the transformer PS imposes these variations in current upon the current oscillations in the circuit GLS, which is arranged to be in the critical state; that is, the oscillations are near the point of ceasing. Current in one direction in S will then cause a large increase

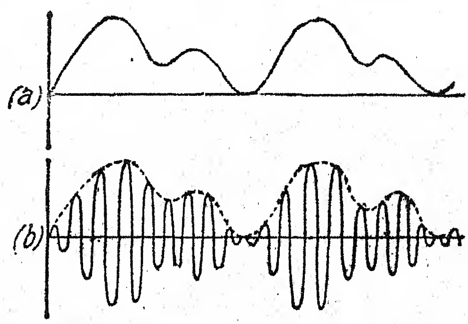


FIG. 115. Modification of the electromagnetic waves for wireless telephony.

in intensity of the oscillations, while the opposite current in S would correspondingly decrease their intensity. In this sensitive condition the variations in current cause very large variations in the intensity of the electromagnetic waves radiated from the aerial. This effect may be illustrated by the curves in Fig. 115. The curve (*a*) is intended to represent the current in the coil P, due to the air vibrations of speech acting on the microphone M. The curve (*b*) indicates the electric oscillations in the aerial circuit, whose fluctuations in magnitude are a copy of the fluctuations in current in P and M (Fig. 114). When the waves emitted reach the receiving station, and the current in the receiving aerial is properly rectified, the diaphragm of the telephone

receiver will execute movements which are a copy of the movements of the sending diaphragm, due to the speaker.

Wireless telephony is now an everyday fact, and it has one very great advantage over the older system of telephony by current carried along wires or cables. For, as we saw in Chapter VIII, the human voice does not consist of simple vibrations but of many vibrations of different frequencies, varying from two or three hundred vibrations per second up to a thousand or more vibrations per second, and it is the mixture of these different frequencies which gives the character to the voice, and determines the nature of the sounds of ordinary voice. It will be remembered also that in Chapter VIII it was seen that waves of current in a cable were attenuated to an amount depending on their frequency or wave-length. Thus, a wave corresponding to a particular sound in ordinary speech is a compound of many constituent waves of different frequencies, and if these components are attenuated to different amounts, the resulting wave received may bear very little resemblance to the wave transmitted. Hence speech transmitted over a cable 500 miles long may be quite unrecognisable. No such difficulty occurs in the case of wireless telephony, for the electromagnetic waves all travel with the same velocity, whatever their frequency may be, and are diminished from various causes all to the same extent, so that at the greatest distance at which radio-telephony has been attained, speech is as easily recognised as over short distances. Of course, many causes may disturb or limit the transmission, but distortion as known in ordinary telephony is not one of them.

Before closing this chapter, something must be said about the forms and sizes of aerials used in various cases, and about a novel method of using the short electromagnetic waves known as light for the transmission of sounds. The ordinary simple mast or wire used in the early days of radio-telegraphy is inefficient, for several reasons. On referring to Fig. 93, it will be seen that the

oscillatory current flows up and down the antenna; but, of course, the current is greatest near the spark gap and gets less and less towards the top of the antenna. If the whole current could be made to flow to the top and down again in each oscillations, the radiation from the antenna would be much more intense. In order to produce this effect, imagine a large condenser to be placed at the top of the antenna, so that the condenser in discharging in an oscillatory manner (p. 152) sends current up and down the antenna. The current at all parts of the antenna will then

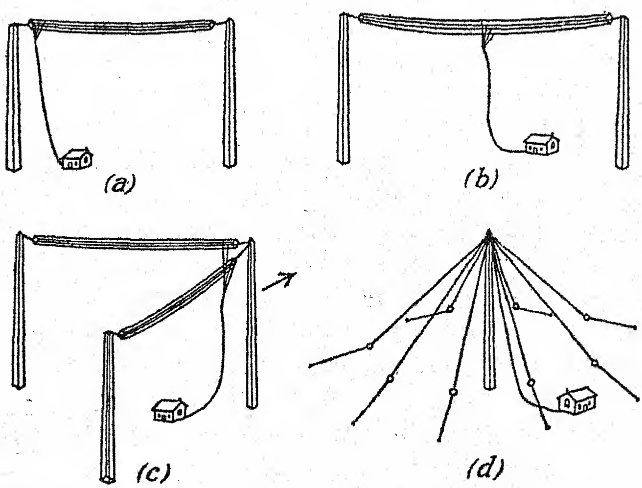


FIG. 116. Various forms of aerial for wireless.

be the same, and the radiation from it will be much more effective than from a simple antenna. For this reason it is usual to attach the antenna to a horizontal system of conductors or wires. There are several ways of doing this, four of which are illustrated in Fig. 116. (*a*) is known as the inverted L form of aerial, and (*b*) the T form. In the type (*c*) there are two horizontal stretches of wire meeting at an angle, and this form has a decided directive effect; the radiation is more intense in the direction to which the angle points than in any other. (*d*) is known as the

umbrella type. It is of the greatest importance that the lower end of the vertical or actual radiating wire should be very carefully connected to earth. It is usual to sink a number of metallic plates in the ground where the earth is moist, and thorough metallic connection is made with them.

Much work has been done of recent years to eliminate atmospheric disturbances. Electromagnetic waves of unknown origin frequently disturb the reception of wireless, and although they may be distinguished by their irregularity from the proper signals, they may at times be so intense that they mask the required signals. Owing to freedom from irregularities, transmission over sea is much easier than over land. Also the useful range for signalling at night is about twice the day range, and the atmospheric disturbances are greatest at dawn and sunset. There is little doubt that the upper layers of the atmosphere are fairly good conductors of electricity. It is well known that as the pressure of a gas is reduced, an electrical discharge takes place through it much more readily than at the ordinary atmospheric pressure (p. 190). Electromagnetic waves will not travel through gas having appreciable electrical conductivity, but will be reflected by such a layer, just as they are by a metallic conductor. As the electromagnetic waves spread out from a station, they would consequently be confined to a layer of space situated between the earth or sea and the conducting layer, whose altitude may be taken as from 100 to 200 kilometres. This layer, sometimes called the "Heaviside layer," prevents the waves from travelling in straight lines and wandering away from the earth. Thus, by making the waves follow the curve of the earth's surface, the range of wireless telegraphy is rendered much greater than it would otherwise be. Radiations from the sun would necessarily disturb the Heaviside layer, which effect accounts for the limited range of transmission by day compared with the night range, and the confusion which arises from the transition from the day

to the night conditions and vice versa. Appleton demonstrated the existence of the Heaviside layer by sending out impulses, which were detected after reflection from the layer: the interval between sending out the impulses and picking up the reflection enables the height of the layer to be determined. Appleton also detected a further conducting region, known as the Appleton layer, above the Heaviside layer. The lower limit of the latter is at a height of about 80 km. and the atmosphere above this is known as the *ionosphere* (p. 206).

The problem of direction finding by wireless is one of considerable importance, especially in navigation. When the ordinary type of aërial is used as receiver, it is impossible to tell the direction from which the electromagnetic waves come, although their origin may be known from the frequency of the waves, and also by the use of code calls for the particular sending stations. The aerials shown in Fig. 116 (*a*) and (*c*) both emit a more intense radiation in the direction of the end of the horizontal portion to which the vertical wire is attached than in any other direction, and to this limited extent the radiation is uni-directional. The problem of finding the direction from which waves come has been partially solved by using a loop or coil of wire wound on a rectangular frame as receiving aerial. If the plane of the frame faces the oncoming waves, no effect is produced; but when the frame presents one edge to the waves, a maximum of reception is attained. By rotating the frame until there is silence in the telephones, the line of the incident waves is known. To discriminate between the two opposite directions which are possible, a single wire aerial has been put in series with the frame, which produces oscillations of such phase that they increase the effect when the frame points one way towards the source and diminish it for the other, thus enabling the true direction to be identified. The importance of being able to ascertain the direction from which the waves come is well recognised, and by means of the direction finder described, it is possible to

determine this direction within a degree or two. This has been the means of giving its position to a fogbound ship, whose direction from two fixed land stations is found from direction finders and then signalled to the ship.

In designing an installation for wireless telegraphy many things must be taken into account, such as range, frequency (or wave-length), height and form of aerial, and power of station supply. These quantities are known with some degree of accuracy. For example, for transmission over sea a distance of 400 kilometres with T aerials 30 metres high, a wave-length of 600 metres (frequency$=$500,000) would be suitable and the power required for constant service about 500 watts, or $\frac{2}{3}$ of a horse-power.

In addition to telephone reception, it is possible to receive by means of the siphon recorder (p. 96) or by some form of relay, so that the message may be printed on the Morse inking machine. When it is not necessary to depend upon the reading of Morse signals by the telegraphic operator, which limits the speed to 20 or 30 words a minute, the use of more rapid methods of sending become possible. The Wheatstone perforating machine has been used at wireless stations, where great numbers of messages have to be dealt with, so that the sending can be carried out at the rate of 100 to 200 words a minute. As this method has been described in Chapter VII, its application to wireless need not be described in further detail.

The advent of the triode has rendered telephonic communication with aircraft a comparatively simple matter, a trailing wire as aerial being quite effective. In this way it is quite easy for a pilot to be in continual touch with his base, and the many advantages resulting from this are sufficiently dealt with in the public press.

There have been many attempts to utilise a beam of light for transmitting sounds, and the method is therefore optical rather than electrical. But the method of reproducing the sound from the fluctuation in intensity of the beam of light depends upon the peculiar electrical properties of

the element selenium. This substance changes in electrical conductivity when light falls upon it, the increase in conductivity depending upon the intensity of the illumination. The selenium, in a very thin layer, is mounted so that it can be placed in circuit with a telephone receiver and a battery of a few cells. The selenium layer with its holder and terminals is generally called a SELENIUM CELL, but the name is not a good one, because the word "cell," used in connection with the subject of electricity, is generally used to designate the source of electromotive force, as described in Chapter IX.

The employment of a beam of light for transmission of

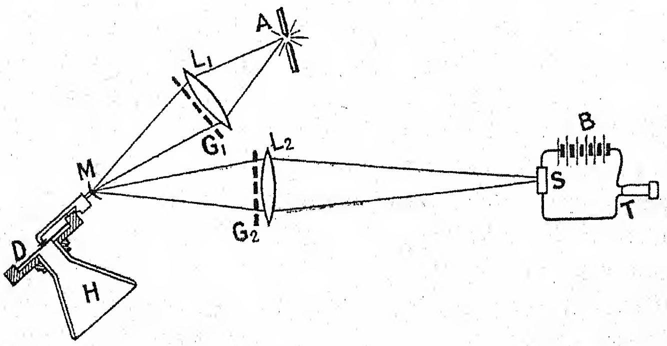


FIG. 117. Rankine's method of transmitting sounds by means of a beam of light.

speech is, of course, a wireless method, but it must not be confused with the method of wireless telephony in which the amplitude of the electromagnetic waves emitted by an aerial is modified by a microphone, as described on p. 179. Prof. A. O. Rankine has devised an arrangement for modifying the intensity of a beam of light so that transmission of speech may be effected over a mile or so. Light from a bright source A (Fig. 117) falls upon a lens L_1 and is brought to a focus on a little concave mirror M. This mirror reflects the light to the lens L_2 which brings it to a focus at the distant station, which effect may be assisted by other lenses if necessary; the optical arrangements are not

described here in detail. At the receiving station is the selenium cell S, with battery B and telephone receiver T in circuit. The novelty of Rankine's method lies in the manner in which the intensity of the beam of light is caused to vary by the air waves of speech. G_1 is a set of opaque lines or grid, seen end-on in the figure, with transparent spaces between the lines. At G_2 is an exactly similar grid, and the distances of the two grids from the mirror M are arranged so that M throws an image of the grid G_1 upon the grid G_2. Now it follows that if the light passing through the clear spaces of G_1 falls upon the opaque lines of G_2 it is all stopped and none gets to S. But if the light from the clear spaces of G_1 falls upon the clear spaces of G_2 it gets through and proceeds on its way to S. Thus a very small shift of the image of G_1, as it falls upon G_2, influences the amount of light which proceeds to S to a very large extent. M is attached to a lever, the other end of which rests on a diaphragm D, like that of a gramophone, and sound waves entering the horn H are therefore able to make the mirror M vibrate in time with themselves, and so to impress corresponding fluctuations on the intensity of the beam of light proceeding to the selenium cell. With this arrangement speech has been transmitted for distances exceeding a mile, with excellent clearness. With intense source of illumination, such as the sun, and improvements in design, the range can be considerably extended.

A further interesting feature may be noted; for if the image of the source, interrupted by the voice waves, as explained above, be allowed to fall on a sensitised cinematograph film, the intensities of the images produced after development in the ordinary way will form a permanent record of the variations in intensity of the beam of light. If, then, the film be passed before the selenium cell, so that a strong beam of light falling on the cell is made to traverse the images, the light falling on the selenium will vary in intensity in the same manner as the original beam. The response of the selenium will therefore reproduce the

original sounds in the telephone, and the film has thus played the part of the record of an ordinary gramophone.

A sound track obtained in this way may be carried at the edge of the film used for photographing scenes, so that a simultaneous record can be obtained of the scene and the sound accompanying it. Upon running the film through a suitable projector, the scene may be thrown on a screen while the sound is heard, thus giving a "talkie-film."

Selenium cells have been largely superseded by what are known as "photo-electric cells." When ultra-violet light falls upon a negatively charged zinc sheet, the surface emits electrons and loses its charge. A similar phenomenon is observed when the alkali metals are illuminated by ordinary light. This is the origin of the photo-electric cell, which consists of a hemispherical sensitive layer A, Fig. 118, of sodium, potassium or, more usually, caesium, contained in a vacuum or in a neon-filled tube and connected to the negative pole of a battery B.

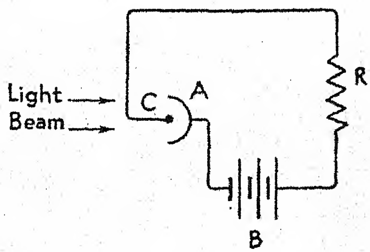


FIG. 118. Photo-electric cell.

The anode C of the cell is a conducting rod arranged at the centre of the hemisphere. Light falls on the surface A, which emits electrons, thereby giving rise to a current in the resistance R. If this is connected to the grid of a triode valve, the plate current through the valve may be caused to vary with the light falling on the surface A. Such cells have many applications, one of the most important being in television (see p. 207). One interesting application is a burglar alarm: an infra-red source of light is arranged at one side of a path and a photo-electric cell at the other. The beam of light falling on the cell maintains a current in the resistance R, which is applied to the grid of a valve, the output current of which maintains closed an electric relay. When anybody walks along the path and interrupts the light beam,

the current in the resistance R falls and the relays open to close a bell or other alarm circuit. Similarly, a photo-electric cell may be used to shut down a printing machine when the moving web of paper breaks, or it may be utilised to maintain the speed of travel of such a web at a precise rate. In the latter case, the paper web, P, Fig. 119, passes between the cell C and the light beam A. Regularly spaced opaque spots S on the edge of the web produce an impulse in the relay R as they pass successively between the light beam and the cell C. If the speed of the web is

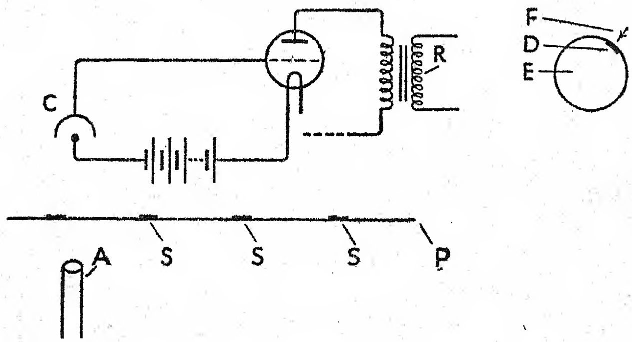


FIG. 119. Photo-electric cell for controlling the speed of travel of a web of paper.

correct, these impulses are produced at a time which coincides with the arrival of an insulating strip D on a rotating commutator E at the contact F. If the speed is too great or too small, the impulses arrive before or after the strip D reaches the contact F and a current flows in one or other of the two circuits which affect the speed of operation of the motor feeding the paper web. Other applications are in timing races, detecting foreign matter in otherwise uniform bodies, counting the number of persons passing a given point, automatically opening or closing gates and so on.

CHAPTER XI

Gases and X-Rays

THE work of Maxwell brought to a close one particular era of development in our knowledge of electricity and at the same time opened the next era. The ingenuity and perseverance of Faraday laid the foundation of understanding the interaction of an electric current and a magnetic field. But Faraday, although he gave a vivid picture of the processes that he considered to be going on whenever action occurred between a magnetic field and a conductor, never attempted to give his ideas quantitative precision. Perhaps the most important development in the mathematical theory of electricity between the time of Faraday and that of Maxwell is due to Kelvin, in his calculation of the manner in which the charge from a condenser will leak away through the conductor which joins its plates. This had an important effect in the realisation of electromagnetic waves, which ultimately led to wireless telegraphy and telephony. The era following Maxwell is characterised by two parallel lines of development, and, while that leading to electromagnetic radiation has been followed in Chapter X, we must now turn our attention to the other. This latter, although it may not be so useful commercially as the former, has led to a profound modification of our knowledge of the constitution of matter, and in this prolific field of investigation it must follow that developments of the highest practical service will result.

Many investigators had been struck by the beautiful phenomenon of the passage of an electric current through a rarefied gas. Faraday himself had noticed that on passing a current or electric discharge, as it is frequently called, through a glass tube in which the air had been rarefied,

certain distinctive effects always occurred. On pumping the air out, to lower the pressure, and passing a current between two platinum terminals K and A (Fig. 120) by means of an induction coil which produces a high electromotive force, the successive changes in the character of the discharge may be observed. When very little air has been removed, the track of the current is luminous, and consists of a sinuous path, like a lightning discharge, and at the same time a crackling noise is heard. On removing more air, the discharge passes more easily, it becomes straighter, and the crackling ceases. When the pressure in the tube has been reduced to about a quarter of the ordinary atmospheric pressure, the stream has broadened considerably and is coloured pinkish or lavender. On reaching a pressure of about one-hundredth of an atmosphere, these

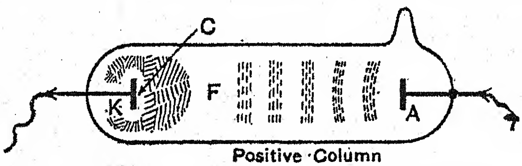


FIG. 120. Electric discharge at moderately low gas pressure.

changes have proceeded further, but in addition, a distinct difference between the two ends of the discharge is observable. The luminous column extends quite up to the anode A (Fig. 120) at which the current enters the tube, but before reaching the cathode K, by which the current leaves, there is a distinct break in the column, constituting a dark space F. Faraday noticed this dark space near the cathode, and it has been named after him the FARADAY DARK SPACE. Between the Faraday dark space and the cathode is a slight bluish glow called the CATHODE GLOW. This was as far as Faraday could proceed, because the means for rarefying the air still further were wanting in those days.

The Geissler tubes, which exhibit this effect so beautifully, are merely tubes in which a current passes through gas at a moderately low pressure; but different kinds

of gas give variously coloured discharges which fill the tube.

The red neon lamps which are now so commonly used for advertising consist of discharge tubes containing neon gas at low pressure: the tubes can be formed into letters or other shapes and as the bright glow fills the whole space in the tube very striking effects can be obtained. If argon is used a pale blue light results, while if a little mercury vapour is added a brilliant blue light is obtained. Helium produces a yellow-white light which is very like ordinary daylight. The effect can of course be suitably varied by using coloured glass for the walls of the tube, or by applying a coating of luminescent or fluorescent material to the inside or outside of the tube. Such material responds particularly to ultra-violet radiation, that is, the part of the spectrum situated beyond the violet. When the discharge takes place in mercury vapour, the radiation is rich in ultra-violet rays, and the gaseous filling of fluorescent tubes therefore most frequently consists of argon at a few millimetres pressure to start the discharge and mercury vapour at a few thousandths of a millimetre pressure to provide the ultra-violet rays. The colour of the light depends on the materials used for the fluorescent coating. Thus, cadmium phosphate gives a red colour, zinc beryllium silicate fluoresces orange or yellow, while zinc silicate is green and magnesium tungstate is blue. White light is obtained by a selection of suitable powders, the proportions of which are varied to give the desired quality of the light.

Among others, Hertz endeavoured to find the explanation of the wonderful effects of the discharge through gases at low pressures. It was thought by all who contemplated this discharge that the proper understanding of it would reveal the explanation of many other phenomena, but no one could imagine the profound extension of knowledge which would eventually follow from the unfolding of the mystery contained in the discharge tube.

A great advance was made by Sir William Crookes on

carrying the exhaustion of the tube to stages beyond that attained by previous experimenters. At a pressure of about a thousandth of an atmosphere, the Faraday dark space F (Fig. 120) separating the cathode glow from the rest of the discharge, called the positive column, has increased, and the positive column itself has become resolved into luminous discs separated by dark spaces, which luminous discs are known as striations. But more important than these is a second dark space, appearing between the cathode glow and the cathode, discovered by Sir William Crookes, and named after him, the CROOKES DARK SPACE C (Fig. 120). Further exhaustion of the tube causes the scale of the whole phenomenon to grow. But it *grows from the cathode*, the other parts disappearing as there is no longer room for them in the tube. First, the positive column goes, then the Faraday dark space, then when the cathode glow goes too, the Crookes dark space fills the whole tube. It is with considerable difficulty that the current can be made to pass through a tube exhausted to such a great extent that the ordinary phenomena of the discharge are absent, the Crookes dark space alone remaining. It might at first sight be thought that this dark space is a mere void, in which nothing is occurring; but Crookes found that this is not the case. Many minerals, if situated in it, glow brilliantly, each with a characteristic colour. In fact, the walls of the glass tube glow with a brilliant greenish yellow if the tube is made of soda glass, and a pale blue if the tube is of lead glass. Further, an obstruction between the cathode and the walls of the tube casts a shadow on the walls, showing that something is travelling outwards from the cathode, which on striking the walls of the tube causes the luminescence. Crookes also showed that a light and delicately suspended body is driven away from the cathode as though it experienced a pressure. Obviously, something in the form of rays is travelling outwards from the cathode producing the effects observed. The general name of CATHODE RAYS was given to them, but whether they

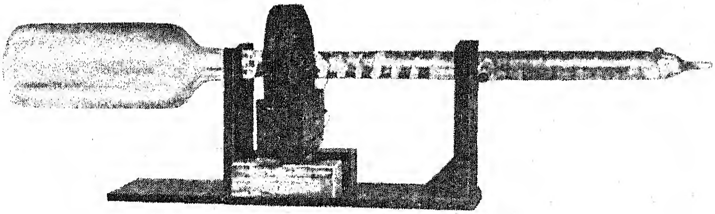
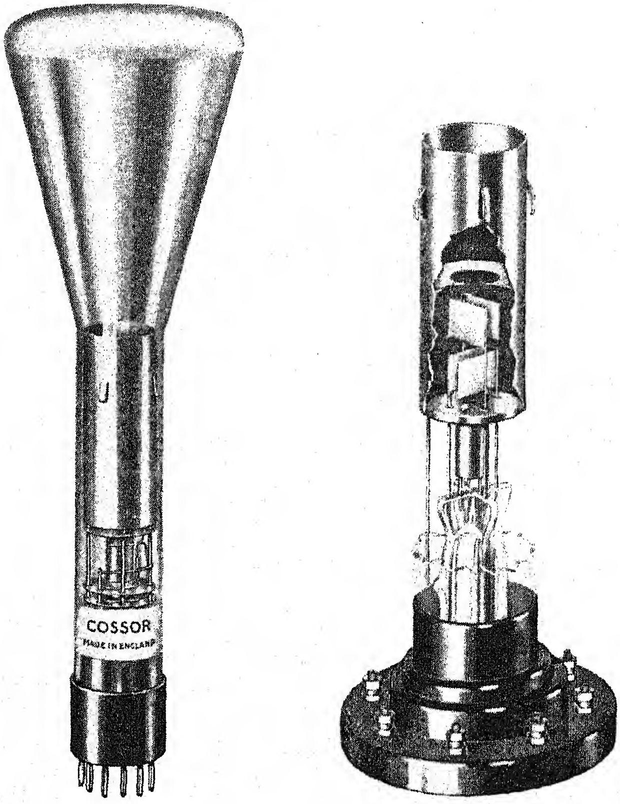
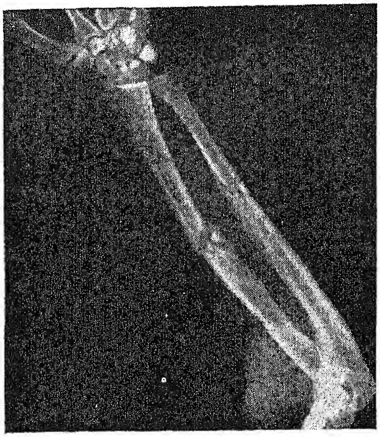


Fig. 124. High voltage Braun tube



(a) (b)

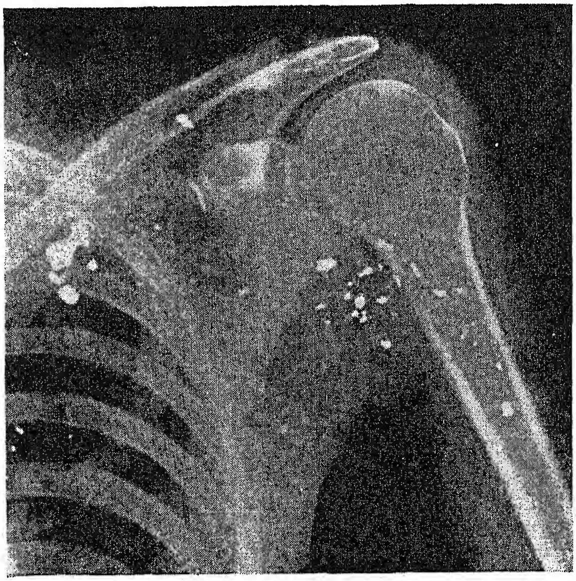
Fig. 125. (a) Low voltage cathode-ray oscillograph
(b) The electrode system



(a)

Fig. 134. Radiographs showing:—
(a) Fracture of fore-arm
(b) Left shoulder. A gunshot wound showing metallic fragments

(b)



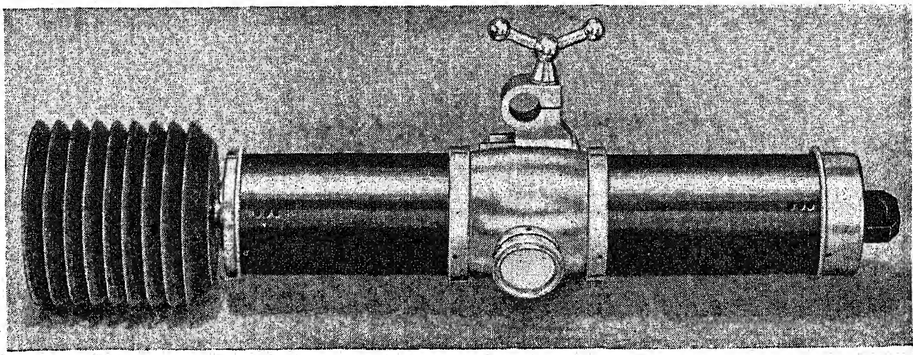


Fig. 135. Goliath X-ray tube

consist of particles of matter shot out from the cathode, or of waves such as light, was at that time an open question. Crookes hazarded the guess that in the dark space was matter in a *fourth condition*, that is, it was neither solid, liquid, nor gas. The guess was prophetic, as it was afterwards found that the cathode rays consisted of matter in a form hitherto unsuspected.

Rays consisting of waves, such as light, are entirely undeflected by a magnetic field, but a very simple experiment serves to show that a comparatively feeble magnetic field will cause a bending of the cathode rays. On cutting the cathode rays down to a narrow beam by means of a metallic screen A (Fig. 121) in which a slit has been cut,

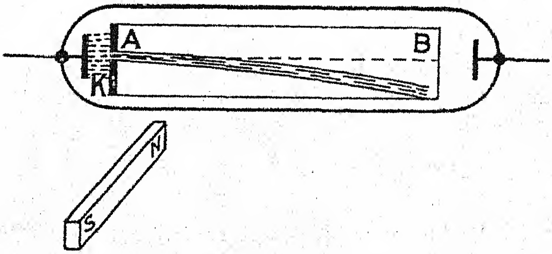


FIG. 121. Bending of the cathode rays in a magnetic field.

and allowing the beam to travel nearly parallel to a metal sheet AB upon which a layer of zinc sulphide has been spread, the track of the beam is marked by a vivid blue band, because the rays cause a blue luminescence in this substance. Under ordinary circumstances the band is perfectly straight, showing that the cathode rays travel in straight lines. But if the pole N of a magnet is brought near the tube, the band becomes curved, showing that the rays experience a force, at right angles to the rays and also at right angles to the magnetic field. It will be remembered that this is exactly the kind of force which an electric current experiences in a magnetic field (p. 41). The ordinary laws which apply to an electric current under this condition lead to the conclusion that, if the cathode

rays do really constitute a current, it must be a current of *negative electricity*, because the rays are obviously travelling away from the cathode, and the direction of the deflection by the magnet is opposite to that which a positive current would experience. It is therefore concluded that the cathode rays consist of bodies having charges of negative electricity, travelling away from the cathode. This conclusion is quite in accord with the other properties of the rays, and is corroborated by the fact that if the rays are caught by a hollow conductor placed to receive them, the conductor is soon found to have acquired a charge of negative electricity.

The proper understanding of the nature of the bodies which constitute the cathode rays we owe chiefly to the work of Sir Joseph J. Thomson, who found their velocity by measuring the displacement produced by a magnetic field and also that produced by an electrostatic field. In the latter case, the negative charges of these bodies are repelled by a negatively charged conductor and attracted by one positively charged. Without mathematical discussion it is impossible to follow the reasoning by which the quantities concerned were measured, but it was eventually found that the velocities of the cathode ray particles were of the order of 30,000,000 metres per second, although this velocity varies under different conditions. But the most important result of these investigations lies in the fact that these particles are of the same nature, whatever the kind of gas which fills the tube, or whatever the material of which the electrodes are made. Also their mass is only about one two-thousandth part ($\frac{1}{1850}$) of the mass of the smallest quantity of matter which had hitherto been known; that is, the mass of the atom of hydrogen. The name of ELECTRON has been given to these bodies. Many workers have contributed to our present knowledge of their mass, notably C. T. R. Wilson at Cambridge and Prof. Millikan in America.

The cloud experiments of Wilson supplied one of the

most important links in the chain of reasoning and experiment by which the actual mass and electric charge of the electron were found. The experiments of Sir J. J. Thomson had given the velocity of the electron, and the ratio of its mass to its charge, but the actual values of the mass and charge were still uncertain. It is true that from the value of this ratio, it was suspected that its mass was of the order of one-thousandth of the mass of an atom of hydrogen, but as no quantity of any material as small as this had ever been detected as having an independent existence, it became of the greatest interest to establish its value by experimental means. The reasoning employed is somewhat as follows: the current through an ionized gas (p. 209) could be measured, and if the velocity of the ions could be measured, and the number present could be found, it follows that the charge upon each ion could be calculated. The velocity was found by many observers without any great difficulty, but the number of ions present in the gas and available for carrying the current was first determined by the cloud experiment. It had long been known that air saturated with water vapour and suddenly cooled gave rise to a cloud or fog, the moisture condensing to form small drops. These drops, however, require some small body, such as a dust particle, to form upon. In dust-free air, cloud or fog is not formed. Again, every small drop falls through the air at a rate depending upon its size, so that if a cloud is produced in an enclosed vessel and then allowed to settle, the drops drag the dust particles down, and will, after a few repetitions of the cloud formation, free the enclosed space, so that no cloud will be produced. C. T. R. Wilson's discovery consists in the fact that if the dust-free air be ionized by means of passing X-rays (p. 209) through it, a cloud may be produced again quite easily, and he showed that the ions produced by the X-rays acted in a similar manner to dust particles in the formation of the cloud. From the work done in cooling the air, the total amount of water condensed could be calculated, and from

the rate of settling of the cloud, the size and mass of the drops is known, so that the number of drops formed is obtained by dividing the mass of water formed by the mass of each drop. Now each drop had an ion as nucleus, so that the number of ions present is found. This completes the chain of argument, and enabled the charge on the electron to be evaluated. In Fig. 122 (*a*) (Plate IV) photographs are shown of the passage of a beam of X-rays through air saturated with water vapour, taken by an apparatus of improved form by C. T. R. Wilson. The drops formed by condensation on the separate ions can be detected. This is probably the first method by which bodies as small as the ion have been individually observed. The method was afterwards improved by Millikan, who, by means of an electric field, separated one drop from the others and afterwards measured its rate of fall, so obtaining a more exact value for the electronic charge than had been previously found. In Fig. 122 (*a*) (Plate IV) the spider's web-like lines each represent the track of an electron, or β particle (p. 255), and are seen to consist of a succession of dots, each dot representing a cloud formed by condensation on the ions produced when the electron strikes an atom of the atmosphere. Fig. 122 (*b*) (Plate IV) is an exceedingly beautiful photograph of the same process and is more magnified than (*a*).

The charge of electricity associated with the electron is the same, whatever the source of the electron, and it is exactly the same as that carried by an atom of hydrogen or any other mono-valent element met with in electrolysis (see Chapter IX). The electron appears therefore to be not only found universally, but to be the ultimate or smallest part of electricity which exists. Every atom contains electrons, some of which are fixed to it and one or more of which may be detached from it. With its complete number of electrons an atom is electrically neutral; when it loses an electron, which is of course a negative charge, it becomes on account of this loss positively charged. The atom

consists of a central positive nucleus with a number of groups of electrons moving in orbits round it. Thus, the hydrogen atom consists of unit nuclear charge and one electron. The helium atom has nuclear charge equal to two units and two electrons surrounding it. Other atoms are built up in a similar way, but the third electron forms the beginning of a second outer ring; additional electrons build up this second ring until they reach eight in number, when the next electron forms the starting-point of the third ring, and so on. The electrons in the outermost ring are most easily detached, and when this occurs the atom loses a negative charge and is left itself with a positive charge. The electrons can move from one ring to another and in doing so give up specific quantities of energy which account for the particular radiations produced by an ionized gas in a discharge tube. It is difficult to estimate the enormous strides made in the understanding and explanation of electrical phenomena by the discovery of the electron. One of the greatest mysteries was, for a long time, the conduction of electricity through metals and the phenomena allied to it. Although perhaps the earliest discovery, that electricity could traverse metals, the secret of the solid state was profound. The electrons in the outermost energy levels of a metal atom are only loosely held by the central nucleus so that they require very little energy to detach them. When, therefore, metal atoms are closely packed together as in a metallic rod or sheet, the outermost electrons are relatively free to move from atom to atom within the solid. The metal may be regarded as composed of ionized atoms with an equal number of free electrons: the ions are fixed and are arranged in a lattice pattern through which the free electrons move when an electric field is applied to them. The motion of the electrons is, however, impeded by collisions with the ions in the lattice and at each collision energy is given up which is converted into heat; in consequence, when a current passes along a metal wire, the latter is heated. The ions in the

lattice are themselves not stationary, but are in a state of thermal agitation; if the temperature of the metal is raised, the ions move about to a greater extent, thus increasing the chances of collisions between the electrons and the ions. As a result, as the temperature of the metal rises its resistance increases. On the other hand, when the metal is cooled sufficiently, the thermal motion of the ions may become very small and the electrical resistance becomes virtually zero. The metal is then said to be "supra-conducting." If an electric current is caused to flow in a ring of metal which has been cooled to this "supra-conducting" state, it continues to flow almost indefinitely without any battery or other external means to maintain it.

In insulating materials, on the other hand, the electrons are tightly held in the space lattice of the atoms and even those in the outer rings can only be moved through very small distances by an electric field and are not detachable from the atom so that when the field is applied no electrons move along the material. In this way the conductivity of some materials and the insulating power of others is explained. Many other electrical properties find a similar explanation, but their consideration will be found elsewhere.

In the discharge tube it becomes clear that the current flowing through the gas consists, at least in part, of a stream of electrons passing from cathode to anode. When an atom loses an electron it must become positively charged, because it was neutral before losing the electron. It would be expected, on these grounds, that positively charged atoms should be present in the gas. Their detection, however, is a matter of difficulty, because they would be urged in the direction of the cathode by the electric field maintaining the current in the gas, and would reach their greatest velocity near the cathode, where the field is most intense. The mass of even the smallest of such bodies, the hydrogen atom, is nearly 2000 times as great as the electron, and its velocity in the electric field would consequently be much less than the electronic velocity.

Moreover, it strikes the cathode at the end of its travel, and would therefore escape detection.

It occurred to Goldstein, in 1886, to perforate the plate constituting the cathode, so that the positively charged particles could pass through it by reason of the momentum acquired in the electric field. He observed faint streamers of light behind the cathode, which obviously consisted of streams of these particles. They are called CANAL RAYS from the mode of their production.

Immediately after the discovery of the existence of the canal rays it became of interest to apply to them the same methods that were so successfully applied by Sir J. J. Thomson to the cathode rays. The deflection of the canal rays by an electric field is an easy matter, and shows, from the fact that they are deflected in the opposite direction to that for the cathode rays, that they are positively charged bodies. Owing to their greater mass and smaller velocity they are not so easily deflected by a magnetic field as are the cathode rays. Much stronger magnetic fields are required to produce measurable deflection, but when these are applied, the measurements show that the bodies constituting the canal rays are the atoms of the gas used in the discharge tube. Also, some of the atoms have lost one electron and therefore have a single positive charge, some have lost two electrons and therefore have a double positive charge. In fact, with mercury vapour, some of the atoms of mercury are found to have as many as eight of these units of positive charge. By a modification of his original method, and using a very high vacuum in the discharge tube, Sir J. J. Thomson was enabled to identify, not only the atoms of various gases, but groupings of atoms, called molecules.

A further improvement of the method by F. W. Aston has enabled spectra of the canal rays, or positive rays, to be produced, in which the lines corresponding to various kinds of atom are arranged so that the equal spacings between them correspond to equal increases in mass of the atoms. The most significant fact about those lines is that they are

separated in most cases by distances which indicate distinct jumps of two in the atomic weights. Also in some cases a given element will be represented by several adjacent lines showing that it may exist with several different kinds of atom, and the ordinary substance, which to the chemist was previously considered to consist of simple atoms all alike, is in reality a mixture of atoms, differing in atomic weight by two from each other. Such varieties of atoms in the case of a substance have been named ISOTOPES. This removes the anomaly of the elements which depart from the whole numbers, since the mixture of isotopes would have an atomic weight intermediate in value between the extreme values for the separate atoms. The theory that all matter consists of atoms built up in various ways from hydrogen atoms has, therefore, been resuscitated by the phenomena of discharge through gases.

Returning to the cathode rays, the fact that these consist of a stream of negatively charged particles which are deflected by a magnetic or an electrostatic field is the basis of a very delicate instrument known as a *cathode-ray oscillograph*, which is used for a number of important purposes. An oscillograph is an instrument for studying the variations of electromotive force or current with time, and various mechanical instruments are known, among which may be mentioned the Duddell and Einthoven types. No mechanical instrument can, however, be employed even at moderately high frequencies without considerable elaboration, and for frequencies above 1,000 per second this type of instrument is practically useless, if only on account of the inertia of the moving parts of the oscillograph and its own natural frequency.

In the cathode-ray oscillograph the moving part takes the form of a jet of electrons, which is not only equally sensitive to all frequencies but constitutes also an inertialess system. The essential parts of a cathode-ray tube consist of the electrode system K, Fig. 123, for producing the electron jet; the anode plate A, which is provided with an

aperture through which the jet passes; the deflecting plates P, which usually comprise two pairs of plates, one pair vertical and the other pair horizontal, to which the various voltages to be studied are applied, thereby producing a deflection of the negatively charged electrons constituting the beam, with consequent movement of a fluorescent spot produced by the impinging of the electrons on a screen S. In Fig. 123 one of the pairs of plates has been replaced by a pair of coils mounted adjacent to the side walls of the instrument which are used when current variations are to be studied. The whole structure in the case of a low-voltage gas-filled tube is mounted in a glass vessel usually shaped as shown in

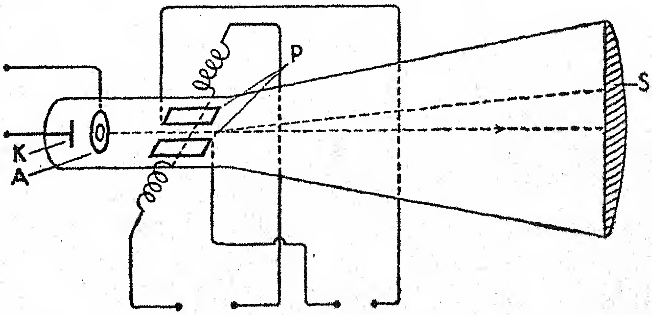


FIG. 123. Cathode-ray tube.

Fig. 123 and filled with an inert gas at low pressure. The first cathode-ray oscillograph was designed by Braun, who produced a cathode-ray beam by applying a high potential difference between two electrodes in a hard vacuum tube. A photograph of such a tube is shown in Fig. 124 (Plate V). The cathode rays were formed into a beam by passing through a small aperture in the diaphragm situated near the anode and finally fell on a fluorescent screen arranged at the end of the tube. The varying magnetic or electric fields were caused to deflect the beam and the consequential movements of the fluorescent spot were studied oscillographically by means of a rotating mirror in which the spot was reflected.

The tube constructed by Braun in 1897 was a somewhat crude piece of apparatus and has since been modified in various ways. One of its principal faults lay in the high voltage necessary to produce an efficient cathode-ray beam but this difficulty was largely overcome by Wehnelt in 1905 by the introduction of a heated lime-coated filament which served as a strong emitter of electrons. By this means, the potential difference between anode and cathode could be very much reduced, the voltage applied being necessary only to speed up the electrons emitted by the filament. This gave rise to a low-voltage tube, i.e. one employing an anode accelerating voltage between 300 and 3000 volts. A low voltage tube of this type is shown in Fig. 125 (Plate V). On the right is shown an enlarged view of the electrode system, which is surrounded by a cylinder known as the Wehnelt cylinder and used for focusing the beam. The residual gas in the tube also serves to assist the focusing and to discharge the screen, which becomes negatively charged by the impact of the electrons forming the beam. The screens are formed of different substances according to their use. For photographic purposes a calcium tungstate screen may be employed, giving a deep blue response suitable for fast photography and also well adapted for visual purposes. Cadmium tungstate gives a pale blue response of remarkable actinic value and without afterglow, and this being the nearest approach to a white light is suitable for television experiments, although a willemite screen having a green response may be used.

If currents are to be studied these are applied to external coils suitably arranged adjacent to the tube, but when voltages are in question, the plates mounted inside the tube are employed. The deflection depends upon the length of the tube, the length of the plates or coils, their distance apart, and upon the voltage or current applied. If a potential difference is applied to one pair of deflecting plates the fluorescent spot on the screen is deflected in one direction; if another potential difference is applied to the other

pair of plates, a deflection at right angles to the first is obtained. By applying a steadily increasing potential difference to one pair of the plates in Fig. 125, the fluorescent spot may be caused to move steadily across the screen; if the potential difference is then suddenly reduced to zero the spot returns to its initial position and the process can be repeated. By this means, a straight horizontal line representing the time required for the potential difference to grow from zero to its maximum is obtained on the screen. A simple time-base circuit for giving this steady potential increase followed by a sharp fall is shown in Fig. 126. The condenser C is charged at a comparatively slow rate

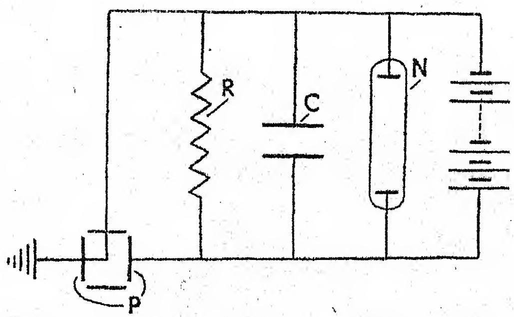


FIG. 126. Time base circuit.

through a resistance R and discharged rapidly when it has reached a voltage sufficient to deflect the spot across the screen. The voltage across the condenser which is applied across the horizontally deflecting plates P of the cathode ray tube takes the saw-tooth form shown in Fig. 127. The condenser may be discharged by means of a rotating commutator switch or alternatively by means of a neon-filled discharge tube N, which passes a heavy current when it lights up at a critical voltage but does not conduct below this voltage. More satisfactory forms of time-base have been devised using a *thyratron* valve, which is a gas-filled, three electrode thermionic valve, having a critical striking voltage which is varied by altering the grid bias on the valve.

It is sometimes desirable to use a different type of time-base and for this purpose a circular, elliptical or spiral curve may be obtained. A circular time curve may be produced by applying an alternating voltage to a resistance and a condenser in series. The voltage across the condenser is then 90° out of phase with that across the resistance. These two voltages are applied simultaneously across the two sets of deflecting plates of the oscillograph and the resulting trace is an ellipse whose major and minor axes are given by the maximum values of the voltages across the resistance and the condenser. The voltage to

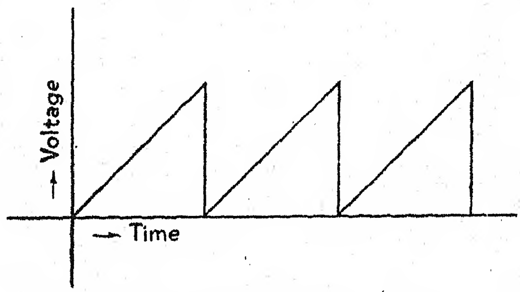


FIG. 127. Saw-tooth voltage wave.

be investigated may be superimposed on either of the two sets of deflecting plates.

If an ordinary straight-line time-base is used and an alternating voltage is applied to the other pair of deflecting plates, the fluorescent spot traces out a curve showing the change of the voltage with time. This is of course a sine wave. Fig. 128 shows the result obtained when an alternating voltage of 50 cycles per second was applied to a small electrodeless tube containing neon gas. The sine wave indicates the voltage across the tube: the vertical lines were the separate discharges through the tube which took place during each voltage cycle, while the upper horizontal line indicates the time-base without any vertical deflecting voltage, and the lower line the deflection produced when a steady bias of 10 volts was applied to the vertical deflecting

plates. These four curves were obtained by four successive exposures of the one photographic plate and the results illustrate the exactitude with which the fluorescent spot repeats its movements on each cycle, thus producing a steady picture which can be seen and photographed.

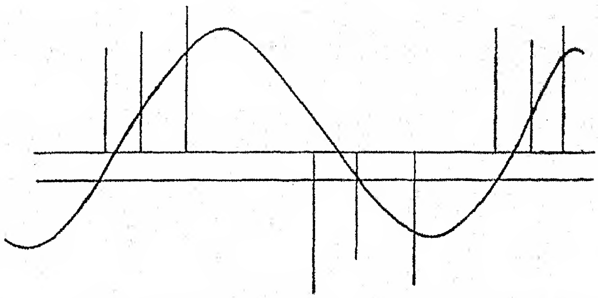


FIG. 128. Oscillogram of current and voltage for a discharge in an electrodeless neon tube.

The cathode-ray tube has been described in some detail because of its great and still growing importance. It is not restricted in its application to the investigation of electrical phenomena, but forms a useful and convenient means of delineating the changes of any variable which can

FIG. 129. Oscillogram of stresses in a concrete pile.

be converted into a proportional electrical quantity. It can therefore be employed in mechanical engineering for studying such matters as stresses in members, torsional oscillations, indicator diagrams and so on. Fig. 129 shows an oscillogram of the stresses set up in a concrete pile with a 1000 lb. hammer. By means of a piezo-electric crystal

(which generates a voltage when it is subjected to mechanical stress), the stresses in the pile are converted into voltage differences which are applied to the deflecting plates of a cathode-ray tube. The oscillogram shown in the Figure indicates a peak compression of 4200 lb. per sq. in. followed by a period of tensile stress in which the peak tension is 800 lb. per sq. in. A time indicator is obtained from the 1000-cycle trace below the oscillogram. A piezo-electric crystal can be used whenever it is desired to investigate mechanical strains and pressures in this manner.

Speech wave forms can be readily shown on an oscillograph by using a microphone the output of which is applied to one pair of deflecting plates while the ordinary time sweeping voltage is applied to the other pair of plates.

FIG. 130. Oscillogram of ionospheric echoes.

This has been used recently in connection with some interesting experiments on fish to determine whether they make audible sounds.

The cathode-ray tube is also used for recording radio atmospherics and ionospheric echoes and for measuring ionospheric heights. Fig. 130 shows a record at a receiving station of ionospheric echoes following a short pulse transmitted from a broadcasting station. The first pulse shows the direct ground ray and the others are echoes from the ionosphere. From the speed of the photographic recording film, the space between the ground ray signal and the echoes and the velocity of propagation of the electromagnetic wave (all of which are known or can be determined) the height of the ionosphere can be calculated.

The same principle can be applied to a direction-finder. The outputs from two fixed frame aerials mounted at an angle of 90° to each other are passed through two separate amplifiers and are applied separately to the two sets of deflecting plates of a cathode-ray tube. The resulting trace of the spot is a line, the inclination of which gives the direction of the incoming signals with respect to the orientation of the frame aerials. When this is applied to collision prevention at sea, the ship sends out short pulses which are reflected from an obstacle and the reflected waves are picked up by the two aerials. If the direction of the signal line remains steady, the ship is in a direct line with the obstacle and a collision will occur unless the path of the ship is changed. The application of this device is of great value in avoiding collision in fog. "Radar" is a development of this principle: an aeroplane transmits the pulses which are reflected to a varying degree according to the surface of the ground or water beneath the aeroplane from which reflection takes place. By causing the emitted pulses to sweep across an area, a picture or map of that area is obtained on the cathode-ray tube screen.

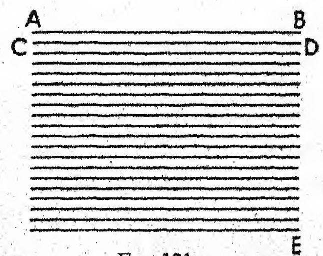


FIG. 131.

One of the most important applications of the cathode-ray tube is to television transmitting and reception, the basic principles of which are as follows. A cathode-ray beam is focused on a cinema film or transparent plate photograph of the scene to be transmitted and behind the film or plate is a light-sensitive cell on which the beam falls. The beam is moved backwards and forwards over the film and is at the same time caused to travel downwards over it; the path traversed is a series of parallel and nearly horizontal lines as shown in Fig. 131. The beam first travels along AB, is deflected back quickly to C, and then travels along CD. This is repeated until the point E at the bottom

corner of the picture is reached, when it is deflected back again to the point A. By this means the whole picture is traversed and is divided up into narrow strips, the whole process being repeated 25 times or more in a second. The beam falls on the photo-electric cell, but its strength depends on the degree of transparency of the film through which it passes—thus a black spot on the film passes little light and consequently generates only a small current in the photo-electric cell. On the other hand, a clear part of the film does not diminish the strength of the beam and a large current flows through the cell. A varying current is therefore produced, the variations of which reproduce the light and shade of the picture which is being televised. This current is used to modulate a carrier wave which is radiated and is picked up by the receiving aerial, connected to a second cathode-ray tube.

The current which is picked up by the receiver may be used to control the second cathode-ray tube by applying it to the deflecting plates of the tube, but it is more usually employed to control the brightness of the fluorescent spot on the tube screen by applying it to the Wehnelt cylinder (p. 202). This cylinder surrounds the beam and serves to focus it; when sharply focused the spot is brighter than when it is not. The focusing effect of the Wehnelt cylinder depends on the voltage applied to it, so that as this voltage is varied a brighter or less bright spot is produced on the tube screen.

At the receiving end of the television set there is, therefore, a cathode-ray tube the fluorescent spot of which is caused to traverse the screen in synchronism with and in precisely the same way as the spot at the transmitting end. The varying voltages produced at the transmitter are applied to the Wehnelt cylinder of the receiving tube and cause a corresponding variation in the brightness of the spot as it traverses the screen. A picture is thus produced which corresponds to that on the film or plate which is being televised.

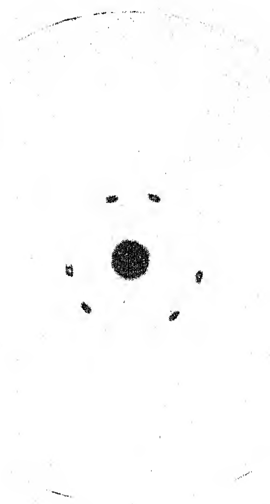


Fig. 136. Diffraction picture obtained by passing X-rays through zinc blende crystals

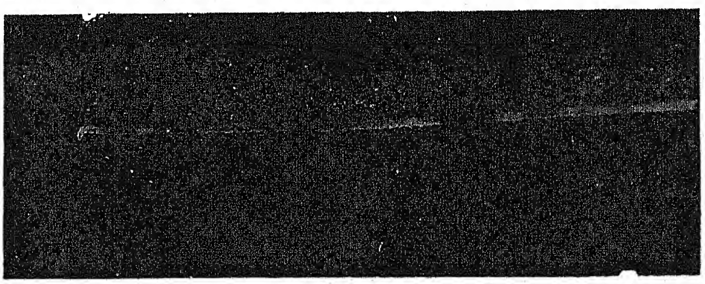


Fig. 138. Photograph by C. T. R. Wilson of the track of an α particle from radium through air supersaturated with water vapour

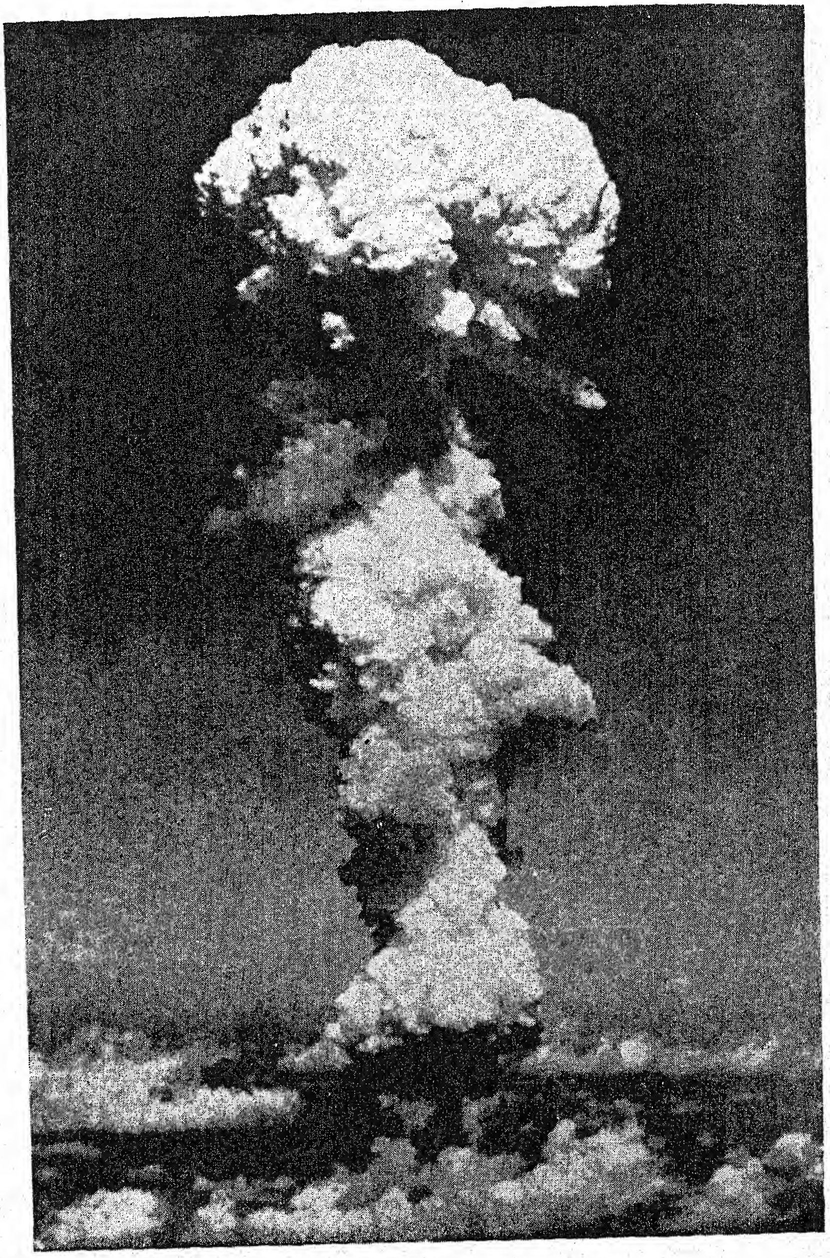


Fig. 140. Atom bomb explosion at Bikini. The blast damaged more than half the seventy-three ships which composed the fleet exposed to the test

Cathode rays have one very important property which has not yet been mentioned and which must now be considered. In the year 1895, Professor Röntgen found that certain photographic plates which had not been exposed to light were, nevertheless, "exposed"; that is, on developing the plates in the ordinary way, they were found to have been acted upon as though by light. The only possibility seemed to be that, as they had been situated near a discharge tube at work, they were affected by some unknown rays which had the same effect upon them as light, but, unlike light, these rays could penetrate the cases in which the plates were contained. A more careful investigation showed Röntgen that such rays were emitted from the discharge tube, and since these rays were of an unknown kind he called them X-RAYS, to emphasise their unknown character. They have since been called both Röntgen rays and X-rays, but the latter name has been, by custom, more particularly attached to them. It was found that whenever cathode rays fall upon a dense material, the point of impact is a source of X-rays, and that these rays can pass easily through the glass walls of the discharge tube and through most ordinary substances. The penetrability of substances by X-rays depends almost entirely upon the density of the substances; those of small density are highly penetrable, while a small layer of a dense material, such as lead, will prevent the passage of any appreciable quantity of the rays. The presence of X-rays may be detected in two ways: by their action upon the photographic plate and by the fact that when they pass through any gas, they cause it to become a conductor of electricity. All pure gases are practically non-conductors of electricity, but when a gas has been rendered conducting by the passage of X-rays through it, it is said to be IONIZED. The former of these two methods, the photographic, has led to most important applications of X-rays for photographic purposes, while the latter or ionizing effect has played the more important part in investigating the nature of the rays, and led eventually to

the new and vast region of scientific knowledge known as radioactivity.

The phenomena of ionization of gases have led to such great steps in our knowledge of the understanding of the nature of matter, that it is necessary to describe them somewhat in detail. All pure gases such as oxygen, nitrogen or air, are non-conductors of electricity, and the simplest method of exhibiting this property is to make use of the gold leaf electroscope. This consists of a pair of leaves of thin metallic foil C (Fig. 132) suspended from a wire B. The leaves may be of gold, aluminium, or any other metal that is procurable in the form of thin light leaf. The wire

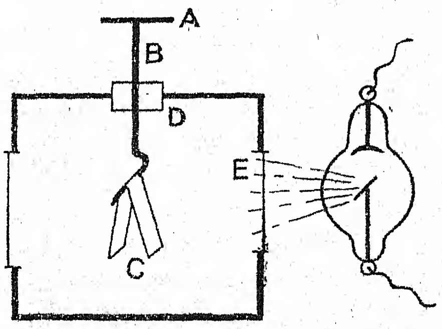


FIG. 132. Measurement of the ionization produced by X-rays.

and leaves must be well insulated by passing the wire B through a supporting block of sulphur or of paraffin wax D, which will not conduct electricity when its surface is kept clean. At the upper end of B is usually a metallic knob or plate A, and the whole is carried by a metallic box having windows, one of which is seen at E. On rubbing a piece of amber or, better, a rod of ebonite with dry fur, the rod becomes electrified, and on bringing it into contact with A, some of the electricity is communicated to A. Owing to the conductivity of A, B and the gold leaves C, the charge of electricity becomes distributed over them, and the leaves will stand apart, as shown in the figure, because the charges on the two leaves, being of the same kind, repel each other.

The leaves will remain charged for a considerable time if no conducting material is brought into contact with the electroscope. But if A is touched by a wire, the charge of electricity escapes at once and the leaves collapse instantly. Even substances which we should call bad conductors for ordinary electric currents, are found by this delicate test to be moderately good conductors. Thus, on touching A with the finger the leaves collapse instantly, the charge passing away through the hand and body; but if dry wood or cotton held in the hand be put in contact with A, the leaves collapse slowly, showing the poor conducting power of these substances. The fact that the leaves will remain charged for a long period shows that the air in contact with the electroscope is an almost perfect non-conductor, for if the block D is in good insulating condition, the charge will remain for hours, with very slight loss.

On placing an X-ray tube opposite one of the windows of the electroscope so that the X-rays enter the chamber, the leaves instantly collapse, showing that the charge of electricity has been conducted away with great rapidity. A similar result may be obtained by leading air from the neighbourhood of an active X-ray tube through a wide tube into the chamber of the electroscope, which shows that the collapse of the leaves is due to the fact that the passage of X-rays through the air has converted it into a conductor of electricity. The air soon recovers its insulating property and on repeating the first experiment with the X-ray tube moved further away from the window, it will be found that the leaves still collapse, but more slowly. The effect can still be observed with the X-ray tube many yards from the electroscope, provided that the X-rays pass through the window, but the collapse of the leaves becomes slower and slower the further the X-ray tube is removed.

We have seen that when the air in the electroscope has been rendered a conductor of electricity it is said to be IONIZED. It was pointed out on p. 196 that matter consists of atoms which consist of a central positive nucleus

with one or more electrons moving in orbits round it. When the gas is ionized by X-rays, an electron is detached from the atom. The remainder of the atom is therefore deficient in negative electricity by the amount of that detached, and is said to be positively charged. Remembering, then, that positive and negative charges of electricity attract each other, the escape of charge of the electroscope can now be understood. For whichever the sign of the charge of electricity on the leaves, that is, whether it be a positive or a negative charge, it will attract the charges of opposite sign in the gas. If the leaves are positively charged they will attract the electrons, which, being negative electricity will, on reaching the leaves, neutralise the positive charge upon them. Similarly if the leaves are negatively charged they will attract the positively charged remainders of the atoms, which will neutralise the negative charges on the leaves; in either case the leaves become discharged. The electrons and the positive remainders of the atoms of the gas are generally called IONS, negative ions and positive ions; hence the word "ionization" as applied to a gas when in this conducting condition produced by X-rays.

Under normal conditions, every atom has its full complement of electrons, the proof of which is that a gas as a rule exhibits no electrical properties. It is completely uncharged, which means that there is exactly as much negative as positive electricity in the whole of its atoms; and it is a non-conductor of electricity, which shows that each atom is exactly neutral; that is, the electrons present constitute an amount of negative electricity exactly equal to the positive electricity associated with the nucleus of the atom. The proof of this lies in the fact that a charged body will remain charged in ordinary air although it is being bombarded millions of times per second by the molecules of the gas.

The difficulty of investigation of the constitution of an atom can be realised by considering the actual sizes and masses concerned. As a rough simile, Lord Kelvin stated

that if a drop of water could be magnified to the size of the earth, the individual molecules would then be about the size of cricket balls. The opposite perhaps appeals to the imagination more. Think of the earth as made up of cricket balls, and then suppose it to shrink to the size of a drop of water. The mind cannot follow the corresponding shrinkage of the cricket balls. Putting it more exactly, the number of molecules in a cubic centimetre of gas under ordinary atmospheric conditions is known from the kinetic theory of gases to be about 27,100,000,000,000,000,000. Each molecule consists of two atoms. The simplest atom, or atom of hydrogen, contains electrons, one of which it can lose, and the electron is only $\frac{1}{1850}$ part of the atom of hydrogen. All the other substances have atoms heavier than the hydrogen atom. The substance with the heaviest atom is uranium, the atom of which is equal in weight to 236·6 hydrogen atoms. Thus the electron is only equivalent to $\frac{1}{437000}$ part of an atom of uranium.

In a very highly rarefied gas, the electron situated in an electric field acquires very great velocity, as we have already seen. But in a gas under ordinary conditions the velocity acquired is not nearly so great, for two reasons. First, the electron soon becomes loaded up with neutral molecules of the gas, which add enormously to its mass, without increasing the force upon it; and, secondly, the ions so produced collide with the other molecules of the gas, so that their progress is not unrestricted as it is in a vacuum. In air at ordinary temperature, the velocity of the negative ions is 1·78 centimetre per second in an electric field of 1 volt per centimetre, and for the positive ion 1·4 cm. per sec. For hydrogen the numbers are 7·43 and 5·4, and for carbon dioxide 0·81 and 0·76. This shows that the larger and heavier molecules amongst which the ions have to push their way restrict their velocity, while the lighter molecules, such as those of hydrogen particularly, do not hinder them so much.

The two streams or drifts of ions through a gas, positive

in one direction and negative in the other, constitute the electric current in the gas, and the reader has probably noticed that the current in a gas bears a great resemblance to the current in an electrolyte, where the ions are pushed through the liquid by the electric field applied by the battery. In fact, the velocities of the ions are similar in magnitude in the two cases. It is likely that all electrical currents, even those in metals, are of this same kind, being a drift or current of electrons, and possibly of positive ions, produced by the applied electric field.

One of the earlier forms of vacuum tube for the production of X-rays is shown in Fig. 133. A glass bulb has an aluminium cathode K and a platinum anode A, set at an angle of 45° to the line joining the two. The tube is exhausted until the Crookes dark space fills it entirely, and, since the cathode rays travel perpendicularly outwards from the cathode, by making this concave, the cathode rays are concentrated upon a small spot of the surface of the platinum anode A. This small spot may even be rendered red hot by the bombardment of the electrons constituting the cathode rays. It is also an intense source of X-rays. This fact may be proved by placing a lead sheet C, with holes *e*, *g*, etc., bored through it, over a photographic plate D. After a short time the plate D is removed and developed, when black spots appear at *f*, *h*, etc., and on replacing the plate and drawing the lines *fe*, *hg*, etc., it may be shown that the rays producing the spots all come from a small region of A.

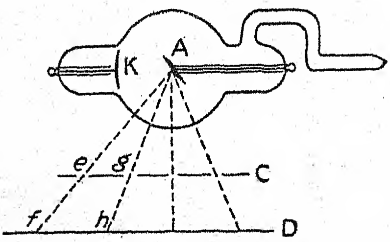


FIG. 133. Early form of X-ray tube, showing how the rays originate at a point on the anti-cathode.

The above method explains the use of an X-ray tube for examining the internal region of bodies in surgery. For if the lead sheet C be replaced by a living limb, the

X-ray shadow cast upon the photographic plate D exhibits the internal structure of the limb. Bony parts, being more dense than the fleshy parts, cut off the X-rays to a greater extent, and so produce lighter parts in the resulting negative. Any foreign metallic body, such as a bullet, casts a sharp shadow and is easily located. In modern X-ray pictures, or radiographs, even the smaller variations in density of the tissues are apparent. Fig. 134 (Plate VI) gives examples of such a case, (*a*) showing a fracture of the forearm, and (*b*) a gunshot wound in the left shoulder.

A modern form of X-ray tube of high efficiency, the Goliath tube, is shown in Fig. 135 (Plate VI). In the older types of tube, the source of electrons for the cathode rays is the residual gas in the tube. After pumping has been carried on to low pressure, the unavoidable variation in the amount of gas present causes irregular working of the tube. For this reason, and to render the behaviour of the tube not only reliable, but under control, the gas is removed until no discharge will pass, and the source of electrons used is a spiral of tungsten wire raised to a high temperature by a local current. We have already seen a similar device used in the case of the triode (p. 174), which revolutionised radio-telegraphy. In fact, the emission of electrons by bodies at high temperatures has become a very important branch of study, most particularly developed by Sir O. W. Richardson, and called THERMIONICS. By means of an induction-coil or transformer, the tungsten is made the cathode for the discharge, and the electrons are driven against a massive anti-cathode or target made of tungsten, from which of course the X-rays arise. For the purpose of focusing the cathode rays upon the target, a shield of the metal molybdenum is used, the shield having various shapes, according to the use of the tube.

The great advance which has been made in the efficiency of X-ray tubes may be realised from the fact that with the early tubes, an exposure of five minutes to half an hour was necessary to obtain a good radiograph, whereas with a

modern tube the times vary from a third of a second, when radiographing the human fingers, to 48 seconds for the head, although, of course, it must be remembered that part of this improvement is due to the advances made in the manufacture of suitable photographic plates, more particularly by adding calcium tungstate to the sensitive film.

It is beyond the scope of this book to enter into any account of the medical uses to which X-rays have been put, but it is worthy of note that not only may metallic objects, fractures and diseases be located, but, by administering opaque insoluble salts of bismuth to a patient in the food, sufficient quantities may be accumulated to render the gullet, stomach and intestines opaque enough to X-rays for their study radiographically. From this treatment many inter-related functions of the various organs have been brought to light. X-rays are also employed for the detection of flaws in wood or metal and faulty weldings between metals. Their range of usefulness is increasing daily.

The nature of the X-rays was for a long time imperfectly understood. X-rays are not deflected by a magnet, and do not carry any electric charge. Hence they differ essentially in character from the cathode rays to which they owe their origin. It was thought at first that they could not be reflected or refracted like light waves, but this has since been accomplished. When X-rays fall upon matter, other or secondary X-rays are found to be emitted, and in late years these secondary X-rays have given us much information upon the constitution of matter. The most important case of reflection of X-rays is that in which the reflection takes place internally in crystals. Light when reflected from a mirror on which very fine parallel lines have been ruled, exhibits patterns, due to the rulings and to the wave nature of light. They are called interference patterns, and are similar in character to the patterns seen on the surface of water when regular ripples or waves are reflected from a wall. These interference patterns are only produced in the

case of waves. In the case of light, they constitute proof of its wave-structure. For many years attempts had been made to obtain interference patterns with X-rays, and the failure to observe them suggested that X-rays might not consist of waves. The failure, however, was due to the fact that no set of rulings, that is, no diffraction grating as it is called, was of fine enough structure to produce interference patterns. It occurred to Prof. M. Laue, in 1913, to try the effect of substituting a crystalline material for the artificially ruled grating employed in the case of light waves. He was rewarded by finding that on passing a beam of X-rays through various crystals, the central beam was surrounded by smaller beams. These produced symmetrically arranged spots surrounding the central spot, when a photographic plate was placed to receive the beams. Fig. 136 (Plate VII) is a typical diffraction picture obtained in this way. This shows that the X-rays are reflected differently in different directions by the crystal, the atomic structure of the crystal being fine enough to act towards X-rays as the rulings of a diffraction grating act towards light waves, although in a more complicated manner. The interpretation of the results presented considerable difficulties, but Sir William H. Bragg succeeded in showing that the structure of the crystal may be discovered by considering the reflection of the X-rays to take place at planes in the crystal which are rich in atoms. In this way one of the great mysteries, that of crystalline structure, has been solved by means of the behaviour of X-rays.

The waves which constitute X-rays are of the same character as light waves, but they are very much shorter. A wave of light is about 0·00006 centimetre long, but the length of a wave in X-rays is about 0·00000001 centimetre. With the exception of the γ-rays (p. 225), and cosmic rays which are produced in outer space beyond the earth's atmosphere, which are of the same nature as X-rays, this is the most minute wave of which we have any knowledge, and it is on account of the smallness, or rather the shortness,

of these waves that X-rays have such great penetrability for ordinary matter.

Cosmic rays entering the atmosphere from outer space are primarily responsible for the ionization of the air, the conductivity of which increases with altitude. As a result of the presence of ions in the air, an electric charge on an electroscope or other instrument always leaks away, no matter how good an insulator is used for supporting the instrument. Cosmic ray particles consist of electrons and positrons in equal numbers.

CHAPTER XII

Radioactivity

It is always difficult to attach the true relative importance to a branch of scientific development. In one branch the application may be wide, or of particular industrial value, so that everyone has a knowledge of it; the newspapers chronicle every advance and the names of those who apply the fruits of scientific research to commercial purposes become household words. Such to a conspicuous extent is the case with wireless telegraphy. But intelligence of other branches of work, of perhaps more profound significance, only reaches the public faintly, and the names of the great workers in such branches are almost entirely unknown outside scientific circles. As a good example of this, the subject of the present chapter may be taken. Radioactivity is a process so widely spread and yet, in its most violent occurrences, so remote from everyday life, that probably not one person in a hundred could give the name of the worker to whom our knowledge of radioactive processes is chiefly due.

In 1896 Prof. Henri Becquerel, of Paris, was examining salts of the metal uranium, to find out what kind of radiation is emitted by them after being exposed to sunlight. Such emission is called phosphorescence, but it must not be confused with the phenomenon of luminescence exhibited by certain substances, particularly those in a state of decay, due to the oxidation of the phosphorus contained by them. The latter process is chemical phosphorescence in distinction to the physical phosphorescence exhibited by diamond, and certain salts such as zinc sulphide, and calcium sulphide, which emit light in the dark for some time after being exposed to bright illumination, a common

example of which is Balmain's luminous paint. Becquerel was examining the substance uranium to see if its phosphorescence was accompanied by the emission of X-rays, as in the case of the glass walls of an X-ray tube, by putting it in close proximity with a photographic plate in the dark, and subsequently developing the plate, the uranium having been previously exposed to sunlight. But it was found that when the uranium had not had any preliminary exposure to sunlight the marking of the plate was still clearly developed. It appeared, therefore, that the exposure to sunlight was not necessary for the emission of the rays which produce the photographic effect. A test experiment was made by producing the uranium salt and crystallising it from the solution in the dark, so that the solid crystals had never been exposed to daylight. The result was just as marked as before; consequently the rays which produce the photographic effect are emitted spontaneously by the uranium salt and are not the result of energy absorbed from light. The name of "Becquerel rays" was given to them, but it was eventually found that they are of such a complex character that the original name gave place to particular names applied to their constituent parts.

The emission of Becquerel rays by uranium was at first difficult to explain. An emission of rays which produce a photographic effect necessarily involves the continual using up of energy, the source of which was not in this case obvious. If the rays were emitted only after exposure to light, it would naturally be thought that the uranium absorbed the energy of the light waves, and afterwards emitted the energy in the form of Becquerel rays. There is no doctrine in science more firmly established than that energy is neither lost nor created in any natural process, but merely changes its form, just as mechanical energy becomes heat whenever there is friction, or chemical energy becomes energy of electric current in the case of an electric battery. Although the origin of the energy of the Becquerel rays was at first unknown, no one at that time felt any

doubt as to the validity of the law of conservation of energy. It was even suggested that the atoms of uranium could catch some form of penetrating radiation which had hitherto remained undiscovered and convert the energy of this radiation into Becquerel rays. It was natural to assume, from general experience, that the atoms of uranium like all other atoms then known, remained constant in mass and in character, which, of course, necessitated the absorption of energy from somewhere before radiation became possible. The mystery was solved at a later time, when it was found that the atoms of uranium do not remain the same after producing radiation. In the act of emitting Becquerel rays, the atoms emit, not only energy, but part of their substance, and are so changed in character that they are no longer atoms of uranium. The energy required for radiation is therefore stored in the uranium atoms, and part of it is used in the emission of the rays; but where it originally came from to form the atom of uranium is still unknown, as the reverse process of building up atoms has never been observed. The disappearance of the uranium is so slow that it would take about 5,000,000,000 (five thousand million) years for any quantity of uranium to decay to half that quantity.

The similarity of the Becquerel rays to X-rays was suspected at an early date, so that the next step in their investigation was to find whether they produced ionization of the gas or atmosphere through which they passed (p. 209). This was found to be the case, and the ionization method turned out to be more convenient for their investigation than the photographic method. The method of the electroscope, which was used for the study of the ionization produced by X-rays, becomes now of the greatest value. There are many forms of electroscope, but one of the best was designed by C. T. R. Wilson and is shown in Fig. 137. The case is of brass, with a glass window provided for viewing the leaf A, which is carried by a brass wire B, supported in a piece of sulphur C. Contact with the leaves

for the purpose of charging them with electricity can be made momentarily by depressing the terminal J. The lower part of the brass case contains a circular opening, which may be closed by a sheet of tissue-paper K, which prevents draughts of air entering the case, but it is not thick enough to stop appreciably the entrance of any radiation from below.

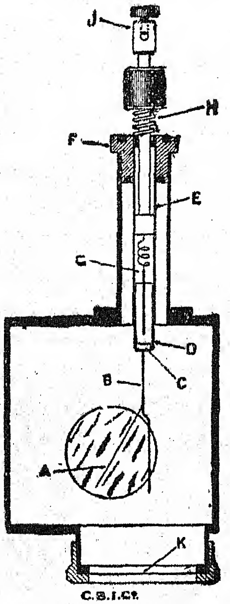


FIG. 137. C. T. R. Wilson's electroscope for studying radio-activity.

On communicating a charge of electricity to the leaf and then watching it, the leaf will be seen to remain diverged from the fixed stem for a very long time. But if a layer of a uranium salt, such as uranium nitrate, is spread on a glass plate and placed under the aperture K, it will be observed that the leaf collapses, falling to its original uncharged position in a few minutes. The Becquerel rays emitted by the uranium can penetrate the thin membrane K and, on entering the chamber of the electroscope, ionize the air inside. The ionization is exactly like the ionization produced by X-rays, and the leaking away of the charge on the leaf of the electroscope takes place in the manner already described (p. 211).

The discovery of this peculiar radiating property of uranium naturally led to a search amongst the other elements, to see whether any other substances have the same power. It was soon found by Schmidt that the element thorium emits Becquerel rays to a similar extent to uranium. Thorium is a rare metal which is an essential constituent of incandescent gas mantles. The ionizing effect of such a mantle may easily be shown by means of the electroscope; and the photographic effect may be exhibited by placing a piece of the mantle in contact with a photographic plate in

the dark for about a week. On developing the plate it is found that the parts intimately in contact with the mantle have been "exposed," and the pattern on the plate forms a very good picture of the structure of the mantle.

The chief source of uranium is the rare mineral pitchblende, which consists principally of uranium oxide. M. and Madame Curie in 1900 undertook an examination of this mineral, and found that the samples obtained from different places had differing activities as regards the emission of Becquerel rays. One specimen, obtained from Joachimstal in Bohemia, was considerably more active than pure uranium, which fact indicated the presence of some other substance in the pitchblende of much greater activity than uranium. They therefore determined to separate the various materials constituting the mineral, a process attended by considerable difficulty. The chemical procedure will not be given here, but the result was that on separating the bismuth from the other substances it was found to present great activity, and the barium was found to be still more active. Now bismuth and barium are not active materials, that is they do not emit Becquerel rays, so that it was obvious that they were mixed with minute quantities of extremely active substances, which no chemical process would separate from them. The barium in the form of barium chloride was therefore dissolved in hot water and the solution allowed to cool until the substance in solution began to crystallise. The part which crystallised out first was found to be the most active. This part was then separated from the rest, redissolved and again crystallised. By a repetition of this process, which is called fractional crystallisation, a small quantity of material was obtained practically free from barium, and its activity in emitting Becquerel rays proved to be very great. After treating several tons of pitchblende in this way, a minute quantity of a new substance was obtained which was found to be a million times more active than uranium. Mme Curie called the new substance RADIUM, on account of

its enormous radioactivity. At each stage of the process of obtaining radium chloride, as described above, the products were tested by means of the electroscope, which offered the surest guide to the presence of the radioactive material. Thus the solution of barium chloride appeared less and less radioactive, as the radium chloride was separated from it by fractional crystallisation, while the parts first crystallised out, since they were richer in radium chloride than the remainder, became more and more radioactive as the process went on.

It will be remembered that the bismuth separated from the pitchblende appeared to be radioactive. By pursuing a similar process, using fractional precipitation instead of crystallisation, Mme Curie obtained another radioactive substance which she named POLONIUM. It was found afterwards that polonium is one of the products of radium (radium F), but it is nevertheless a distinct substance.

Subsequently, A. Debierne succeeded in separating another radioactive material from the uranium group. This he called ACTINIUM. It is closely associated with thorium.

Up to now we have considered the Becquerel rays as though they were of a single type, and had two properties, that of affecting a photographic plate, and that of producing ionization of a gas. In order to understand the processes of radioactivity, it is necessary to examine the nature of the Becquerel rays more closely. Our knowledge of the processes of radioactivity we owe chiefly to the work of Lord Rutherford, and a simple experiment described by him will suffice to prove the complexity of the Becquerel rays. On placing a small quantity of radium bromide below the window K of the electroscope (Fig. 137), it will be found that the leaves collapse very rapidly, owing to the charge of electricity placed upon them escaping. This is due to the ionization of the gas by the rays from the radium, as already described. Now, a layer of tin-foil placed between the radium and the electroscope will cut off most of

the rays, so that the amount of ionization is much less than before, and the leaves collapse more slowly. If they take ten times as long to collapse a certain distance it may be concluded that nine-tenths of the radiation has been cut off, only one-tenth of the original amount being able to penetrate the tin-foil. This is about the magnitude of the effect that would be observed. We should expect that a second layer of tin-foil added to the first would cut down the radiation again to one-tenth, so that it would be one-hundredth of the intensity of the original unobstructed radiation. This, however, is not found to be the case; the second layer of tin-foil produces very little reduction, showing that the rays consisted of a portion of slight penetrating power which was practically all absorbed by the first layer of tin-foil, and a second portion of much greater penetrating power which the tin-foil absorbed only slightly. The part most easily absorbable Rutherford named the α (alpha) RAYS. If the experiment be repeated, using sheets of lead about 2 millimetres in thickness in place of the tin-foil, a similar effect is observed, even if the α-rays have been first removed by a layer of tin-foil. It follows that the rays which penetrated the tin-foil are still complex, consisting of a portion which is almost entirely stopped by the first sheet of lead, which Rutherford called the β (beta) RAYS, and a still more penetrating kind which he called the γ (gamma) RAYS. There are thus three kinds of radiation in the Becquerel rays, called respectively the α, β and the γ rays. The following table, given by Rutherford, shows the relative penetrating powers of the three kinds of rays:

Rays.	Thickness of aluminium which reduces the ionization to one-half.	Relative penetrating power.
α	0·0005 centimetre	1
β	0·05 ,,	100
γ	8·0 centimetres	10,000

The α-rays have many peculiar properties: they affect the photographic plate and they have a very powerful ionizing effect upon gases through which they pass. Also they produce fluorescence in many substances. For example, if a small quantity of radium be brought near a diamond in the dark, the diamond is seen to glow with a bluish light, which simple test serves to identify the stone as a true diamond. Very great use has been made in recent years of the fact that the α-rays from radium cause the substance zinc sulphide to glow with considerable luminosity. The radium paint which has been used for marking the points on the cards of magnetic compasses and for the points on watch dials so that they can be read in the dark, is made by mixing a small quantity of radium bromide with a considerable amount of powdered zinc sulphide. The mixture is made into a paste with a good varnish and painted on the cards, where the varnish sets hard. Unfortunately the zinc sulphide rapidly loses its power of fluorescence, and the luminosity after a year or so has fallen off considerably. On examining the luminous paint under the microscope, it will be seen that what had appeared to be a continuous luminosity really consists of a number of separate flashes, the effect looking like a very beautiful rain of sparks. Sir Wm. Crookes exhibited this effect in a little instrument which he called the spinthariscope. A minute speck of radium bromide is placed behind a thin layer of zinc sulphide which is observed by means of a high-power lens. After resting the eye in the dark for a time and then looking through the lens, the brilliant flashing of sparks may be seen. There is no doubt that each flash is the result of a particle emitted by the radium striking the zinc sulphide. It is now known that the α-rays consist of particles shot off with considerable velocity by the radium atoms, and that these α particles carry positive charges. They are atoms of the light element helium. By using considerable magnification of the zinc sulphide screen it has been found possible, by counting the flashes

in a given time, to find the number of α particles emitted by radium in each second. We have already come across streams of positively charged particles in the case of the positive or canal rays in the discharge tube (p. 199). But whereas the particles in the discharge tube are atoms of the gas in the tube, the particles of the α-rays are positively charged atoms of the gas helium. This is the first case observed in which one kind of substance is produced from another, helium being produced from radium. What remains when the radium atom has lost the atom of helium will be seen later. Since the α-rays consist of rapidly moving charged particles, we should expect that they would be deflected by a magnetic field. This is the case; but owing to their mass being much greater than that of the electron (about 7400 times as great), their deflection for a given magnetic field is much less. Very strong magnetic fields are necessary in order to produce measurable deflection of the α particles, which fact has rendered the determination of their mass of considerable difficulty. Nevertheless, methods similar to those used for the measurement of the mass of the electron (p. 194) have proved successful, and the α-ray particle has been found to have the mass of a helium atom and to carry a positive charge of electricity equivalent to two electrons, but, of course, of opposite sign.

α-rays have another peculiarity, discovered by Sir Wm. Bragg, that the range throughout which they can produce ionization is strictly limited. As they penetrate, in their flight, the molecules of the gas through which they travel, they lose velocity. The fact of breaking the gaseous molecule, through which an α particle passes, involves an expenditure of energy, so that the emergent particle has less velocity than before impact; but, on the other hand, its own mass is considerable, so that its path is very little deflected by the impact. The paths of the α particles through air are therefore nearly straight lines. But when the velocity drops to a certain value, the power of producing ionization

suddenly ceases. Thus the length of the path of an α particle through air depends upon the velocity with which it started from the radioactive material. Since this velocity is different for every material, so far as is known, and the range in air is a measure of the velocity, it follows that the range of the α particle in air serves as an excellent means of identifying the various materials from which the α particles arise; thus, the range of the α particle in air at standard temperature and pressure is given in the table on p. 232, along with the various radioactive materials. In the case of the α particle from radium C, the range in air is 6·94 centimetres and its velocity of emission is 192,200 kilometres per second. Lord Rutherford found that when the velocity of the α particle has fallen to 11,200 kilometres per second, it ceases to have the power of ionizing the molecules of the gas, and hence it is impossible to trace it further by means of this effect.

The properties of the α particles have been exhibited by C. T. R. Wilson in a beautiful manner by allowing them to pass through air which is supersaturated with water vapour, and photographing the cloud track formed by condensation on the ions produced. Such a photograph is seen in Fig. 138 (Plate VII), from which it will be seen that the track of the α particle is nearly a straight line and so differs very much from the tortuous track of the lighter β particle. Also it will be seen that the ionization ends abruptly, the velocity having then fallen to the limit required for ionization.

The β-rays are of an entirely different character to the α-rays. They are, as we have seen, more penetrating, and it was soon discovered that they carried negative charges of electricity. This suggests a similarity to cathode rays, and the discovery of their deflection in a magnetic field rendered their identification an easy matter. They consist of very rapidly moving electrons, the velocity being in some cases as high as 285,000 kilometres per second, which is the nearest approach to the velocity of light, 300,000 kilometres

per second, that has been observed for any moving material. An interesting point has arisen in connection with this; the electromagnetic theory shows that a charge of electricity in motion should have mass, or inertia, merely on account of its motion; but at ordinary velocities this mass is practically constant and independent of the velocity. As, however, the velocity approaches that of light, the mass of the moving charge should increase rapidly. This has been found to be the case with the most rapid β-rays, and the observed increase in mass is quite in accord with that calculated on the assumption that the mass of the electron is of an electrical nature. This observation gives very stong support to the electromagnetic theory.

An interesting application of the properties of β-rays was devised by Hon. R. J. Strutt, afterwards Lord Rayleigh. A small quantity of radium bromide is contained in a sealed glass vessel A (Fig. 139), and two gold leaves in metallic contact with the interior hang from A. The whole is suspended inside an exhausted glass vessel and insulated from it. Now the β-rays, which we have seen consist of electrons, can penetrate the glass walls of A and escape, while the positively charged α-rays cannot. The result of this loss of negative electricity is that the contents of A continually accumulate positive electricity and the gold leaves diverge more and more as the charge accumulates. When, however, the leaves diverge sufficiently, the tips touch the walls of the outer vessel, which are lined with tin-foil connected to earth. This causes the instant discharge of the leaves, which therefore collapse, and the whole process begins afresh. The time that elapses depends only on the quantity of radium present and the rate of absorption of the α-rays by the walls of the vessel, so that the arrangement constitutes a sort of clock, which goes on at the same rate for an indefinite time without requiring any attention. It

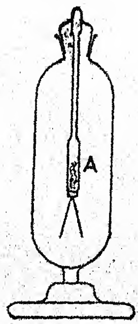


FIG. 139. Strutt's radium clock.

looks at first sight as though perpetual motion had been attained, but of course the radium is gradually being used up, and it would take 1730 years for the amount of radium to become halved.

γ-rays are in all respects similar to X-rays; that is, they have very great penetrating power, they produce ionization of gases, and affect a photographic plate. Also they are not deflected by a magnetic field. For their particular properties, therefore, the reader may consult the section on X-rays. It is of very great interest to note that the three kinds of radiation, cathode rays, positive or canal rays and X-rays, whose existence and properties were discovered in connection with the passage of electricity through highly rarefied gases, were so soon afterwards found to be of natural occurrence in the case of radioactive substances. It is even possible that they are of universal occurrence, for there is no doubt that electrons are at least partial constituents of the atoms of all matter, while the change from one kind of atom to another, which is observed in certain cases, may have given rise to all the forms of matter of which the universe is composed, and we know that such changes are in many cases accompanied by the emission of α, β and γ rays. In fact, it is by the emission of these rays that the transformations have been discovered.

We must now turn our attention to the transformations which have been mentioned in connection with radioactive manifestations. These were first worked out completely by Lord Rutherford for the case of thorium, but many workers have contributed to the elucidation of the changes occurring in the radioactive series of metals as at present known. Amongst these should be mentioned M. and Mme Curie, Prof. Becquerel, and Prof. F. Soddy.

Radioactive transformations, although varying greatly in the rate at which they take place, and in the character of the accompanying radiation, have one feature in common, which is, that the substance undergoing change disappears at a constant rate, and the substance produced disappears

in its turn at a constant rate. To understand what this rate of decay means, suppose that half the molecules of a given substance were to change into another form, with or without the production of radiation, in say 24 hours. Only half the original quantity of substance then remains. In the next 24 hours half of this remaining quantity will change, leaving one-quarter of the original amount remaining. Thus, after the lapse of a further interval of 24 hours only one-eighth of the original amount remains, and after another 24 hours one-sixteenth, and so on. In this case it would be said that the half-value period of the substance is 24 hours. On consulting the table on p. 232 it will be seen that the half-value period of the known radioactive substances varies from 13,000,000,000 years, in the case of thorium, to 0·002 second, in the case of actinium A. The complexity of the products of any radioactive material makes the elucidation of the series extremely difficult, for the substance produced may be a solid, liquid or gas, it may have a long life or a short one, and it may emit α-rays, or β- and γ-rays, or no rays at all, in changing to the next product of the series. Also it may remain embedded in the parent substance, or it may, in the case of a gaseous product, diffuse from it, and it may be separable from the parent substance by physical means such as heating, or by the processes of chemical analysis. In the case of radium, the immediate product is a gas which generally remains in the solid radium, though heating removes this gas, which leaves the radium pure for a short time. But immediately the production and accumulation of the gas in the radium begins to produce a fresh store. The amount of the gas which ultimately collects in the radium depends upon two things, the rate of its production by the radium, and the rate at which the gas itself decays. It is clear that a substance which decays rapidly will never accumulate to any considerable extent, while one which undergoes very slow decay will be present in large quantities when equilibrium is eventually reached. For this reason the minerals

	Time for decay to half-value.	Rays emitted.	Range of α particle in air at 76 cm. pressure and 15° C. in centimetres.
Uranium 1	5×10^9 years	α	2·50
Uranium X_1	23·5 days	β	—
Uranium X_2	1·17 min.	β	—
Uranium 2	2×10^5 years	α	2·90
Ionium	$8{\cdot}3 \times 10^4$ years (?)	α	3·00
Radium	1730 years	α	3·30
Emanation (radon)	3·85 days	α	4·16
Radium A	3·0 min.	α	4·75
Radium B	26·8 min.	β	—
Radium C	19·5 min.	α	6·94
Radium D	16·5 years	β	—
Radium E	4·85 days	β	—
Radium F	136 days	α	3·77
Lead (?)	—	—	—
Thorium	$1{\cdot}3 \times 10^{10}$ years	α	2·72
Mesothorium 1	6.7 years	β	—
Mesothorium 2	6·2 hours	β, γ	—
Radiothorium	1·9 years	α	3·87
Thorium X	3·64 days	α	4·30
Emanation	54 sec.	α	5·00
Thorium A	0·14 sec.	α	5·70
Thorium B	10·6 hours	β	—
Thorium C	60·8 min.	α	4·95
Thorium D	3·1 min.	β	—
Thorium C^1	10^{-9} sec.	α	8·60
Protoactinium	$3{\cdot}2 \times 10^4$ years	α	3·14
Actinium	13·5 years	—	—
Radioactinium	19·5 days	α	4·60
Actinium X	11·6 days	α	4·40
Emanation	3·92 sec.	α	5·70
Actinium A	0·002 sec.	α	6·50
Actinium B	36·1 min.	β	—
Actinium C	2·15 min.	α	6·25
Actinium D	4·71 min.	β	—

which contain uranium and radium and their products will contain much more uranium (half-value period = 5,000,000,000 years) than radium (half-value period = 1730 years), while the gaseous product of radium (half-value period = 3·85 days) will be present in quantities too small to be detected by weighing, and only to be discovered by their radioactivity, which has an intensity corresponding to the rapidity of change. It has been found that an atom of radium in changing gives out one α particle, as does an

atom of the gas produced when it, in its turn, changes. Consequently when sufficient time has elapsed for equilibrium to become established, the rate of production of the gas must equal its rate of decay, and thus the number of atoms of radium that break up in a given time is equal to the number of atoms of the gas that break up in the same time. Hence the number of α particles emitted by radium in a given time must be equal to the number emitted by the gas in the radium in the same time. Since there are, in addition, two other products of the gas which each emit an α particle for each atom breaking up, it follows that the radium only emits itself one-quarter of the number of α particles which the radium and its contained products altogether emit in the same time, provided that equilibrium has been reached. Of course, any removal of one or more of the products from the parent radium will upset the condition of equilibrium, which will only be restored by allowing sufficient time to elapse for the production of the materials removed.

It is impossible to give in the present book an account of all the methods of experiment which led to our knowledge of the radioactive series of elements, but an outline of these series is attempted. There are three such series known, but for a long time there were considered to be four. The uranium series and the radium series were discovered separately, and although it was suspected that radium was one of the products of uranium, its descent was not definitely traced. The constancy of the proportion of the quantity of radium to that of uranium in certain minerals was considered evidence that the latter was the origin of the former, but we now know, beyond doubt, what changes occur which link the two together. The uranium-radium series is the most important of all the radioactive series, containing about sixteen distinct substances. The other two are the thorium series and the actinium series (p. 232).

Uranium is the heaviest substance known to exist in a

natural state, its atomic weight being 238·5. It occurs in many minerals, particularly in pitchblende. The salts of uranium are generally yellow or greenish, the substance being used in the manufacture of canary glass. All the salts are radioactive, that is, they will affect a photographic plate and will produce ionization. Sir William Crookes found, in 1900, that on adding ammonium carbonate to a solution of a salt of uranium, a precipitate is formed which dissolves on adding more ammonium carbonate. On filtering the solution, a minute precipitate is separated from it. This precipitate has a powerful effect upon the photographic plate, and the original uranium has lost this power. On the other hand, the production of ionization is still retained by the uranium. Since the photographic effect is chiefly due to β-rays and the ionizing effect to α-rays, it follows that the substance separated from the uranium emits β-rays. Sir William Crookes called this substance uranium X. It follows that uranium in changing to uranium X emits α-rays, while the uranium X emits β-rays. After the lapse of two or three months the uranium recovers its photographic effect owing to the production of a fresh supply of uranium X, while the separated uranium X entirely disappears. It has since been found that uranium X is not a simple substance. Uranium itself produces uranium X_1, with emission of one α-ray particle. Uranium X_1 has a half-value period of 23·5 days, changing to uranium X_2 with emission of slowly moving electrons. The half-value period of uranium X_2 is only 1·17 minutes, and it emits β-rays, changing to a very long-lived product called uranium 2, whose half-value period is two hundred thousand years, which emits one α-ray particle, changing to a substance called ionium, whose half-value period is eighty-three thousand years. Ionium is the parent of radium, and each atom of ionium emits an α particle in the act of becoming an atom of radium. Thus each atom of uranium emits in all three α particles before it becomes one radium atom. Now the atomic weight of uranium is

238·5, and the α particle is really an atom of helium, which has an atomic weight of 3·99. Thus the loss of three α particles should lessen the atomic weight of uranium by $3 \times 3{\cdot}99 = 11{\cdot}97$, or very nearly 12, and it then becomes 226·5. This is the atomic weight found by direct measurement for radium, which fact is very good evidence in favour of the truth of the deductions made from observations on radioactivity. The β-ray particles, or electrons lost in the radioactive change, are of such small mass that their effect on atomic weight is negligible.

Radium and its immediate changes presents one of the most important and fascinating chapters in the history of science, being found as the result of deliberate search by Mme Curie, and producing the most striking series of products. It has already been mentioned that radium continuously produces a gas, the radium itself having a half-value period of 1730 years, and emitting α-rays during the change. The gas is called radium emanation or radon, which itself has a half-value period of 3·85 days, and also emits α-rays during its change. Radium emanation obeys the ordinary laws of gases, and liquefies at a temperature of $-65°$ C. Its atomic weight is 223, which corresponds very well with that of radium, assuming that each radium atom (226·5) loses an α particle (3·99) in becoming an atom of radium emanation.

Under no known conditions can the rate of change or the activity of a substance be varied; radioactive changes go on at the same rate at the lowest and highest temperatures whether the substance is in chemical combination with another or not, whether it is compressed or rarefied. It was at first thought that radium emanation exhibited an exception to this rule, for on immersing a solid, such as a metal rod, in the gas for an hour or so, and then withdrawing it, the the rod was found to affect an electroscope and exhibit all the properties of a radioactive substance. If the rod be negatively charged with electricity, the excited activity is greater than that upon an uncharged rod. Also the

excited activity can be removed by scraping off the surface of the rod, which shows that the rod has not become radioactive, but that a radioactive substance has been deposited upon it. The atoms must have positive charges, since they are attracted to a negatively charged rod. The substance deposited was called the active deposit, but it was soon seen that it is not a simple substance. The activity of the active deposit falls to a very small quantity in the course of a day, leaving a minute remainder which increases in activity over several years. Three changes are involved in the rapid part of the decay, the first occurring with emission of α-rays and having a half-value of three minutes. The substance is called radium A and is the immediate product of the emanation. The product of radium A is called radium B, which has a half-value period of 26·8 minutes and emits slowly moving electrons, and gives rise to radium C, having a half-value period of 19·5 minutes, in turn becoming radium D, with emission of α- and β-rays. Radium D is a long-lived product and emits slowly moving electrons and having a half-value period of 16·5 years. Radium E has a half-value period of 4·85 days, and also emits slowly moving electrons, while the next product, radium F, emits α-rays and has a half-value period of 136 days. Radium F is a substance of considerable interest, because it was discovered independently by Mme Curie, who called it polonium (p. 224), and also because it is the last of the radioactive products of the uranium-radium series. The atom of radium, with its products, thus loses five α particles in the various transformations, so that the atomic weight of the ultimate product would be $\{226{\cdot}5-(5\times 3{\cdot}99)\}$, that is 206·7. The atomic weight of lead is 207, which fact suggests that the product of change of radium F is lead. The presence of lead in all the uranium-radium minerals confirms this fact; but, so far as is known, lead is not radioactive and is certainly an extremely long-lived substance. Since lead does not emit α, β or γ rays, its change could only be detected by the loss in weight in

lead, which is certainly not within the range of experimental detection. There is no reasonable doubt that lead is the product of radium F, and therefore the end product, so far as is known, of the uranium-radium series.

The thorium and the actinium series do not present the special features of interest of the uranium-radium series. A table of the radioactive changes at present known is given on p. 232.

One of the most interesting facts in connection with radioactivity is the production of heat during radioactive change. The α and β particles are ejected from the atoms with enormous velocities, which in itself indicates a great store of energy in each atom. Owing to the greater size of the α particle, more energy is required to give it its great velocity than in the case of the β particle, and the loss of energy of the atom in ejecting an α particle is probably about ten times that for a β particle. If the α particles are stopped by collision with the atoms in the interior of the radioactive body, heat is produced, and this heat causes a rise of temperature. It follows that radioactive bodies, unless in very thin layers, are always at a higher temperature than their surroundings, which difference in temperature amounts to several degrees in the case of radium compounds. The energy of the α particle has its counterpart in the recoil of the remainder of the atom. If an α particle, whose mass is approximately that of 4 hydrogen atoms, is shot out with velocity of, say, 20,000 kilometres per second from an atom of radium of mass 226, the velocity of recoil of the atom can be calculated just as in the case of the velocity of recoil of a gun when the bullet leaves it. Thus, $4 \times 20{,}000 = 226 \times$ (velocity of recoil), so that the velocity of recoil is 354 kilometres per second. It follows that the energy or heating effect of the α particle is about 57 times that of the recoil atom, and the latter must be added to the former to obtain the whole heating effect. The rate of emission of heat by radium and its products has been measured in several ways, and the

results compare very well with those found by calculating the energy liberated when the α- and β-rays are given out. It has been found that the heat emitted by 1 gramme of radium and its short-lived products, radium emanation and radium A, B, and C, is enough to raise about $1\frac{1}{4}$ gramme of water from freezing point to boiling point in every hour. Considering that the radium continues to give out this heat hour after hour, for hundreds of years, without appreciable diminution, it will be realised that in the radium atoms there must be a vast store of energy. Even when all the radium has changed through the whole chain of products and become lead, it is almost certain that the store of energy in the atom is not much diminished, although there are no means of observing any further changes that may occur. There is no reason to believe that the atoms of the known radioactive materials differ in character from those of other materials, except in the fact that the atoms are less stable and are apt to give off an α or a β particle with alteration to a new internal arrangement. It is probable that every atom contains a heavy central portion with lighter outer portions in rapid rotation round it, in a manner somewhat similar to the solar system of a central sun with planets revolving around it. Some arrangements are possible, others impossible, but some of the possible arrangements are less stable than others. When they are of an unstable form, rearrangements are frequent, as in the case of the short-lived radioactive substances. But with greater stability of form, changes are less frequent, and the substance has a longer life. The ordinary elements constitute the more stable forms, and in the majority of cases the stability is so great that no change has been observed. In the whole life of a gramme of radium, which of course lasts over millions of years, it has been estimated that the total amount of heat given out is enough to raise 37,000 kilogrammes of water from freezing to boiling point. The vastness of the store of energy in the radium may be realised by remembering that the most violent combustion,

that of hydrogen and oxygen to form water, gives an amount of heat which is insignificant in comparison with that given out by radium in the whole of its radioactive changes. For the formation of one gramme of water by the combustion of hydrogen in oxygen causes an evolution of only enough heat to raise about one-third of a kilogram of water from freezing to boiling point. Hence the store of energy in a given weight of fuel is almost nothing in comparison with the store of energy within the atoms. It is clear that if some means could be devised of making the atoms of ordinary substances give up their energy at will, great stores of energy would be liberated which would for example render us independent of coal. Recently great advances have been made in this field following the discovery that radioactivity could be *induced* in most elements by bombarding them with X-rays or with *neutrons*. Curie and Joliot, who bombarded boron, magnesium and aluminium with X-rays, found that these metals became radioactive, although this lasted for a few minutes only. When beryllium was treated in this way it emitted a new particle known as a neutron, which has the same mass as the hydrogen nucleus but carries no charge, and has therefore great penetrative power. At a certain velocity, the neutron is captured by the uranium nucleus which has an atomic weight of 238 to give a nucleus of 239. This is radioactive and loses a β-particle to give a new element of atomic weight 239 known as *neptunium*. This is itself unstable and is radioactive; it loses a further β-particle to form another new element *plutonium* which is also radioactive but is comparatively stable. It is this element which is used in the atomic bomb. Several elements on capturing a swift neutron undergo nuclear fission, whereby the nucleus divides into two parts. The mass of the products is less than that of the original nucleus and the mass which disappears is converted into energy. Plutonium undergoes nuclear fission with neutrons of any energy, and the resultant products are

themselves radioactive: further neutrons are given off which produce nuclear fission in other atoms and an ultra-rapid chain reaction results with the liberation of enormous energy. The reaction takes place only under suitable conditions and with a mass of material greater than a critical size. If the mass is smaller than this critical size it is stable; when two such masses are brought together and nuclear fission is started by means of neutrons, an exceedingly violent reaction takes place and the heat and pressure produced are enormous. The resulting effect is many times greater than that produced by the explosion of an ordinary bomb as is shown by the photograph in Fig. 140 (Plate VIII) of an atom bomb explosion at Bikini atoll.

In due course, no doubt, the energy of the atom will be suitably harnessed and will replace the other forms of energy which are at present employed.

Many speculations as to the source of energy of the sun have been made at different times, and the explanations given are undoubtedly in part true. But the tremendous store of energy within the atoms themselves had played no part in these explanations until recent years. That radioactive changes are occurring in materials present in the sun is extremely probable, for the element helium is present in the sun's atmosphere, in fact, it was discovered there before it was known that it existed on the earth, and we have seen that helium is given off as α particles during many radioactive processes. Another interesting speculation on which our knowledge of radioactivity has shed important light, is that respecting the age of the earth. For many years geologists had maintained, from the examination of fossils, that the age of the earth was much greater than the estimate made by physicists from the known rate of cooling. Treating the earth as a mass of hot material which is cooling by radiating its heat into space, the time that has elapsed since its temperature was first within the limits required for living organisms has been found. But if there is another store of energy, as we see there is in the motions

going on within the atoms, it is likely that the time to cool is much greater than was at first thought. It was estimated by Lord Rayleigh that about 270 tons of radium in the interior of the earth would produce heat at a sufficient rate for the known increase of temperature of 1° C. for every 100 feet depth in the outer layers of the earth. On observing the radium contents of known minerals, it is seen to be not unlikely that such a quantity of radium exists in the earth, so that the rate of cooling of the earth is certainly much slower than was at first thought. The latest estimates of the time for which the earth has been habitable come much nearer the thousand million years required by the geologists than the earlier estimates.

ELECTRICAL TERMS IN GENERAL USE

α-rays. The most readily absorbable part of the rays emitted by radioactive substances. They have positive charges, and eventually prove to be positively charged atoms of helium.

Accumulator. *See* Secondary cell.

Aerial. The vertical conductor in which electrical oscillations occur, and from which the electromagnetic radiations used in wireless telegraphy arise.

Alternating current. Current which flows alternately in opposite directions through any circuit. The number of cycles of current per second is called the frequency, and in common practice is 50.

Ampere. The practical unit of electrical current. It is the current which, flowing in an arc of a circle of unit length and unit radius, causes a magnetic field of one-tenth of a unit strength at the centre. Also 1 ampere flowing for 1 second deposits 0·001118 gramme of silver or 0·000329 gramme of copper.

Amplifier. *See* Triode.

Anode. The electrode by which the current enters the electrolytic cell or gaseous discharge tube.

Arc. The phenomenon exhibited when a current passes continuously across a conducting bridge of gas between two conductors, generally of carbon.

Armature. The rotating portion of a dynamo, in which the current is produced. Also, a piece of iron placed near the poles of a magnet.

Audion. *See* Triode.

Automatic telegraphic working. A method of sending the message by mechanical means instead of working the sending key by hand.

β-rays. Rays emitted by radioactive substances consisting of electrons possessing very high velocity. They are of the same nature as the cathode rays of the discharge tube.

Battery. A number of cells so placed in a circuit that their effect is cumulative. The earliest example of a battery is the Volta pile.

Becquerel rays. The rays emitted by uranium and other radioactive substances. These are now known by the names of their constituents, the α-, β- and γ- rays.

Board of Trade unit. *See* Kilowatt-hour.

Bus bars, or omnibus bars, are thick copper bars provided with terminals and mounted on insulating supports. The supply mains are joined, one to each bus bar, and the separate distribution mains are similarly joined to the two bars.

Canal rays. Streams of positively charged atoms which have passed through apertures in the cathode of the discharge tube.

Cathode. The electrode by which the current leaves the electrolytic cell or gaseous discharge tube.

Cathode glow. The first luminous tract on proceeding outwards from the cathode of the discharge tube. It is bounded by the Crookes dark space on one side and the Faraday dark space on the other.

Cathode rays. Rays in the Crookes dark space, proceeding outwards from the cathode of the discharge tube. They were eventually found to consist of streams of electrons travelling with high velocity.

Cathode-ray tube. An instrument for detecting and measuring variations in voltages, and comprising a glass or other container in which is generated a beam of cathode rays. The beam is deflected by applying the varying voltages to deflecting plates or coils in or near the container.

Cell. The electric cell is an arrangement of conductors and liquids which produces electric current from the energy of the chemical reactions occurring.

Coherer. A loose metallic contact or series of contacts, which falls in resistance when minute electric currents pass through it, thus forming a delicate detector for electromagnetic waves.

Commutator. An apparatus for changing the direction of an electrical current in a circuit in an appropriate manner.

Condenser. A conducting sheet of considerable extent, parallel to and insulated from a similar sheet. The great area required is usually obtained by using alternating layers of tin-foil for the conducting sheets, the layers being separated by paraffined paper or, in the best condensers, thin sheets of mica.

Conductor. A substance which will carry an electric current. All metals and some other substances are conductors.

Cosmic rays. Highly penetrating rays from outer space which produce ionization in the atmosphere.

Coulomb. The practical unit of quantity of electricity. It is the quantity of electricity which flows through a conductor when a current of one ampere flows for one second.

Crater. The hottest part of the positive carbon when the arc is formed. It is cup-shaped owing to the rapid volatilisation of carbon at the high temperature.

Crookes dark space. The dark space immediately surrounding the cathode of the discharge tube, and separating it from the cathode glow.

Crystal detector. A rectifier which produces its effect by allowing the current through the contact of a crystal (generally carborundum) and a metal to pass more freely in one direction than in the other.

Declination, magnetic. The angle between the rest position of the magnetic compass and the true north-and-south direction.

Diamagnetic. A term applied to those substances which when placed in a magnetic field are urged from the stronger to the weaker parts of the field. Among diamagnetic substances are bismuth, antimony, water, silver, gold, sulphur, etc.

Dielectric. *See* Insulator.

Differential galvanometer. A form of galvanometer in which there are two coils, similar in all respects, so that when the same current passes in opposite direction round the two coils, it produces no effect upon the needle.

Differential system. A form of duplex telegraphy in which the working is effected by the use of differential galvanometers.

Diplex system. A system of working in which two messages may be sent simultaneously in the same direction along a line, by using relays of different types for receiving the message.

Direct current. Current which flows always in the same direction.

Dry cell. A cell in which the electrolyte is held in sawdust and glycerine for the prevention of splashing.

Duplex system. A system of telegraphy in which messages may be sent in either direction along a line at the same time without interfering with each other.

Dynamo. A machine for the conversion of mechanical motion into electric current.

Earth. A connection to the ground for the purpose of completing an electric circuit through the earth in order to save one connecting line.

Electro-chemical equivalent. The amount of any substance liberated from solution by one ampere flowing for one second.

Electrode. The conductor by which the current enters or leaves an electrolyte.

Electrolysis. The process of passage of an electric current through certain solutions, accompanied by a decomposition of the substance in solution.

Electrolyte. The solution through which a current passes, with decomposition of the substance in solution.

Electro-magnet. An iron core, surrounded by a coil of wire carrying an electric current and magnetised by it. The core is magnetised only when the current flows in the coil.

Electromotive force (e.m.f.). The property of the source of current in a circuit which determines the current and rate of production of electrical energy in the circuit. Whenever energy can be converted from some other form into energy of electric current, there an electromotive force is situated. (*See* Volt.)

Electron. The ultimate unit part of negative electricity, first discovered in motion as the cathode rays, but now found to be present in the atoms of all matter. The electron theory is the most fruitful of all modern electrical theories. The mass is $8{\cdot}9 \times 10^{-28}$ gramme or $\frac{1}{1850}$ of the mass of the hydrogen atom.

Electrostatics. The study of the properties of electricity at rest.

Faraday dark space. The dark space or gap between the cathode glow and the positive column in a discharge tube at partial vacuum.

Ferro-magnetic. A term applied to the three metals—iron, nickel and cobalt—which have magnetic properties which are several thousands of times greater than those of any other known substances.

Field Magnet. A powerful electro-magnet employed to supply the magnetic field in which the armature of a dynamo or electro-motor rotates.

Flame arc. An arc lamp in which the carbons are impregnated with various mineral substances which volatilise and emit light when incandescent. The long arc has thus the appearance of a flame.

Flashing. A process in the manufacture of carbon filament lamps, in which the filament is rendered uniform, of correct resistance and of good surface.

Frequency. The number of complete vibrations made in one second.

γ-rays. The most penetrating rays emitted by radioactive substances. They are of the same character as X-rays.

Galvanometer. An instrument for detecting or measuring small electric currents.

Incandescent lamp. A lamp in which a fine filament is raised to such a high temperature by the passage of an electric current that light is emitted.

Induction coil. A type of transformer in which the interruption of a current from a few cells in the primary circuit causes an enormously great electromotive force in the secondary circuit. Various devices are used to produce the repeated interruption of the primary current, the most common type being of the trembler pattern.

Induction motor. An alternating current electro-motor in which a rotating magnetic field causes a copper conductor mounted on an axle to follow the rotation of the field. Such a motor is not confined to one speed of rotation as is the case with the synchronous motor.

Insulator. A substance such as amber, quartz, paraffin wax, silk, etc., which will not convey an electric current.

Ionization. The effect of rendering a gas a conductor of electricity by the passage of rays through it. The ionizing rays may be X-rays, α-rays, β-rays or γ-rays.

Ions. The name "ion" is generally applied to a charged particle of a gas when the gas is at ordinary pressure. Both electrons and the positive nuclei of atoms gather neutral atoms about them, and the collection if arranged about a positive charge will be driven in one direction, if about a negative charge or electron in the opposite direction by an electric field. Ions also occur in electrolysis.

Isotopes. Varieties of atoms of an element having atomic weights usually differing by 2.

Kilowatt-hour. The Board of Trade unit of electrical energy. It is the energy supplied in one hour by a power of 1000 watts.

Lead. Any wire or cable leading the current to or from the place at which it is required.

Leyden jar. A convenient form of condenser, made of a glass jar with inner and outer coatings of tin-foil.

Magnet. A piece of iron or steel which has the property of attracting other pieces of iron or steel, and also the property of setting in one definite direction when free to turn.

Magneto. A rotating form of induction coil in which the current in the primary coil is produced as in the dynamo, by rotating a coil of wire in a magnetic field. The spark in the secondary circuit was at one stage commonly employed for exploding the gaseous mixture in the cylinder of the internal combustion engine.

Microphone. An arrangement by which small mechanical movements such as sound waves produce comparatively large variations in electric current. The commonest type of microphone makes use of the varying resistance of carbon contacts due to mechanical disturbance.

Motor-generator. A combination of electro-motor and dynamo in which the former drives the latter. The armatures are usually mounted on the same axle. The motor-generator is most commonly used when the supply is alternating and the requirement is for direct current. The electro-motor is then of the alternating-current type and this drives a direct-current dynamo.

Multiplex system. A system of telegraphy in which more than four messages may be sent over the same line at the same time.

Neutron. A body without electric charge and having the same mass as the nucleus of the hydrogen atom.

Nodon valve. An electrolytic cell in which the current will only pass in one direction. It is used for converting an alternating current into a unidirectional current. It cannot, of course, correct for the fluctuations in value of the alternating current.

Ohm. The practical unit of electrical resistance (*see* Volt). The ohm is the resistance of a column of mercury 106·300 centimetres long and weighing 14·4521 grammes when the temperature is 0° C.

Paramagnetic. A term applied to those feebly magnetisable substances which when placed in a magnetic field are urged from the weaker to the stronger parts of the field. Among paramagnetic substances are platinum, aluminium and many minerals containing iron.

Photo-electric cell. A cell containing a layer of sodium, potassium or caesium which emits electrons when light falls on it, thus producing a current which varies with the intensity of the light.

Polarisation. The deleterious effect of hydrogen deposited upon the positive electrode of a cell when producing current.

Pole (magnetic). The place on a magnet where the external properties of the magnet are most strongly exhibited.

Polyphase current. Alternating current in three or more connected circuits in which the simultaneous currents are not in the same phase.

Positive rays. *See* Canal rays.

Positron. The smallest part of positive electricity known which has the same mass as an electron.

Primary cells. Cells in which the energy required for the maintenance of the electric current is derived from the chemical reactions between the substances of which the cell is constructed. A primary cell is useless when once its constituent materials are used up.

Primary coil. The term is usually applied to one coil of a tranformer or induction coil. It is the coil through which the current passes which is due to some outside source of electromotive force. The result of variation in the strength of current in the primary coil is to produce an electromotive force in the secondary coil. (Also *see* Transformer.)

Proton. The positively charged nucleus of the hydrogen atom.

Quadruplex system. A system of telegraphy in which four messages may be transmitted simultaneously over the same line, two in each direction.

Radar. A method of detecting distant objects such as aeroplanes by electrical pulses which are emitted from a station and are reflected back to that station by the object to be detected, the original pulse and the reflected pulse being recorded by means of a cathode-ray tube.

Radioactivity. The power of emitting spontaneously rays which affect the photographic plate and produce ionization of gases. The radioactive substance loses part of its mass, becoming a new chemical substance, in the act of emitting the rays.

Receiver. The part of a telephonic installation which converts variations of electric current into sound waves.

Rectifier. An arrangement for enabling a rapidly oscillating current to be detected by means of the telephone receiver. It either suppresses entirely the half-wave of current in one direction or, in some cases, allows the half-wave in one direction to be transmitted much more readily than the half-wave in the other direction.

Relay. An electro-magnet or other device by means of which a feeble incoming current or set of waves sets in operation some local source of power and so magnifies the original feeble signal.

Resonator. A conductor for which the natural frequency of electrical oscillation is the same as that of the waves falling upon it.

Rheostat. A conductor placed in a circuit for the purpose of regulating the current. Its resistance is not generally known with accuracy.

it from entering the tubes BC. The condensed mercury is conveyed back to the boiler.

Such pumps may be used in series, each one carrying the evacuation a stage higher than the last. Pressures of a millionth of a millimetre of mercury may be attained rapidly by such pumps.

Exercises on Chapter XI

1. Give an account of the important facts associated with the phenomenon of diffusion.

What do you understand by osmotic pressure, and how may it be explained ? C.W.B.H.S.C.

2. State Fick's law, and deduce from it the fact that the time taken to equalise the distribution of a solute is proportional to the square of the length of column of the solution.

3. Define coefficient of diffusion, and give its dimensions.

4. What do you understand by osmotic pressure ? Describe an experiment by which you could estimate the osmotic pressure of a given sugar solution.

How would you expect your results to vary with (*a*) the concentration of the solution, (*b*) the temperature ? O.H.S.C.

5. Explain the process of effusion of a gas, and account for the fact that the composition of a mixture of two gases is not changed when effusion occurs, while it is changed on diffusion through a porous substance.

6. A mass of 5 grams of a substance is dissolved in 600 c.c. of water. If the molecular weight of the substance is 270, calculate the osmotic pressure.

7. Find an expression for the change in maximum vapour pressure produced on solution, in terms of the osmotic pressure.

8. Explain how the molecular weight of a solute may be determined from the change in boiling point it produces.

9. Define *osmotic pressure*, and describe how the osmotic pressure of a sugar solution may be measured.

The osmotic pressure of a solution containing 6 gm. of cane sugar in 100 c.c. of water is 307 cm. of mercury at 13° C. What is the osmotic pressure of a solution of one-sixth this concentration at 50° C. ?

Lond. Int. Sci.

10. Define *molecular elevation of the boiling point*, and calculate its value in the case of a solvent whose boiling point is 35° C., and whose latent heat of evaporation at that temperature is 81 cal. per gm. and density 0·7 gm. cm.$^{-3}$.

CHAPTER XII

SURFACE TENSION

General description of surface tension.—It is common experience that a very small quantity of a liquid, not subject to outside disturbance, will assume the form of a spherical drop. The fact that falling rain-drops are spheres is proved by the symmetrical form of the rainbow. Now a sphere is a geometrical shape which has the smallest area of surface for a given volume. It thus appears that a drop tends to form itself into the shape with minimum area of surface.

Many other simple phenomena illustrate this tendency to make the area of surface of a liquid as small as possible. For example, if a small paint brush be dipped into water, the hairs of the brush are seen to stand apart, but on raising the brush out of the water, the hairs cling together, owing to the water surface tending to shrink. If a wire ring be dipped into a soap solution and removed, a film may be produced. If two threads AB and CD (Fig. 168) have been previously tied to the ring, the threads being slack, they will not interfere with the film, but will merely slide about in it. On piercing the film between CD and the ring, this part of the film disappears, but the rest remains, and it will be seen that the thread CD is now drawn tightly into a circular form. This clearly indicates that the film tends to shrink, that is, a tension exists in it. The thread AB remains loose, because this tension or pull exists equally on both sides of it.

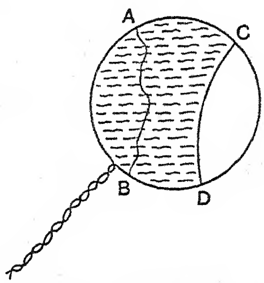


FIG. 168.—DEMONSTRATION OF SURFACE TENSION.

The existence of this pull in the surfaces of the liquid explains all the above phenomena. The surface behaves like a stretched skin,

but with this difference, that for the skin the tension is greater the more the skin is stretched, but the tension in the surface of a liquid is independent of the area of the surface. It is called the **surface tension** of the liquid. It is the force per unit length of a line drawn in the surface and acts at right angles to the line, tending to pull the surface apart along the line. The dimensions of surface tension are given by $\frac{\text{force}}{\text{length}}$ or $[MLT^{-2}.\ L^{-1}]=[MT^{-2}]$.

The simple kinetic theory of gases (Chap. X), when extended to the case of liquids, affords an explanation of surface tension. In that theory the molecules of a gas are supposed to be so far apart that any attraction between them is infinitesimal. It is well known that on compressing a gas, Boyle's law ceases to be true when the density becomes considerable. This is largely due to the fact that the molecules are so close to each other that the effect of their attraction for each other becomes appreciable. On continuing the compression, a stage will be reached at which the effect of the attraction predominates over the tendency of the molecules to fly apart with their indiscriminate velocities. It should be remembered that a liquid can have a free surface, but a gas cannot (p. 154). The reason for this is now seen.

In the interior of a liquid the molecular attractions act equally in all directions, so that a molecule is not urged in one direction more than another; it merely possesses its temperature velocity, although collisions with other molecules are much more frequent than in the gaseous state. Near the surface of the liquid the symmetry of the attracting forces no longer exists. Suppose that the attraction between two molecules ceases to be appreciable when the distance between their centres is c. With the molecule A (Fig. 169) as centre, draw a sphere of radius c. Molecules outside this sphere will not affect A, and those inside it are symmetrically situated, so that the resultant force on A is zero. But at B the sphere of influence lies partly outside the liquid, and this part will only contain the comparatively few molecules of the gas or vapour above the liquid. Hence there is a resultant downward force on B, which reaches its maximum value when B is in the surface of the liquid. If the molecule can pass through the surface, as at C, the downward force becomes less and less until the sphere

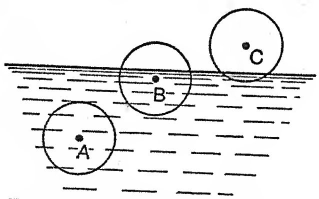


FIG. 169.—MOLECULAR ATTRACTION IN A LIQUID.

of influence leaves the liquid, when the molecule is free to wander as a molecule of the gas or vapour.

All over the surface of a liquid there is thus a pull, due to the attraction between the molecules, tending to prevent their escape. This inward pull near the surface is greater when the surface is convex than when it is plane. For at A (Fig. 170) the lower half EBF of the sphere of influence is intact, and the downward pull due to it is the same as though the surface of the liquid were plane. But the upper part is reduced from the slice CDFE for the plane surface to the piece GHFE for the spherical surface. The upward pull is therefore reduced by the curvature of the surface of the liquid, and the resultant inward pull is increased. Thus the inward pull on molecules near the surface is greater where the surface is most curved and the liquid tends towards the form of uniform curvature, that is a sphere. This is exactly the effect that a tension in the surface would produce, and this explanation indicates that surface tension is a molecular phenomenon.

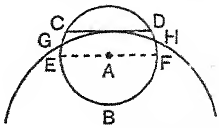


FIG. 170.—ATTRACTION FOR MOLECULES AT A CURVED SURFACE.

In order to extend a surface, molecules must be brought from the interior to the surface. This requires work to be performed. In a similar way, energy is liberated if a surface contracts. This fact shows that every surface has a tendency to contract, and explains the so-called surface tension.

Determination of surface tension by the balance.—The balance affords a direct method of measuring surface tension. Make a wire framework ABCD (Fig. 171) and suspend it from one arm of a balance as on p. 163. Let it dip into a vessel of water as shown, and add weights to the other pan until the frame immersed to EF is counterbalanced. Now dip the frame until AB is immersed, and raise it until AB is just above the surface of the water. The part ABFE will be occupied by a film. On counterbalancing by adding weights until the balance is again in equilibrium, it will be found that the additional weight m is required. The film therefore pulls the frame downwards with a force mg dynes. If the length of EF is l cm. and T is the surface tension of the

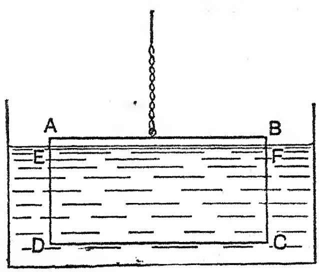


FIG. 171.—BALANCE METHOD FOR MEASURING SURFACE TENSION.

water, the total pull is $2lT$, for the film has two surfaces, each having surface tension T;

$$\therefore\ 2lT = mg,$$

$$T = \frac{mg}{2l}.$$

This may be repeated with the other liquids. The result is not very accurate, because of the difficulty of making sure that the same amount of the frame is immersed each time. Also if the frame is raised too far, the film will break.

Work done in producing surface.—If a film is produced in a frame ABCD (Fig. 172), of which the side AD can slide, the force $F = 2lT$ is required to maintain AD at rest. If now AD is moved to GH, the work done in opposition to F is Fx ergs, that is, $2lTx$ ergs, where x cm. is the distance AD moves. The area of film created in this movement is lx and the new area of surface is $2lx$, for the film has two sides. Thus the work done per unit area of surface in opposition to the force due to surface tension is $\frac{2lTx}{2lx} = T$ ergs per sq. cm. On this account surface tension is sometimes, but wrongly, called the surface energy. If no heat is supplied to the film, it is cooled when AD is pulled outwards. If heat is supplied to restore its temperature, this heat is also part of the surface energy. The term "free surface energy" is often used for the quantity of energy that is numerically equal to the surface tension.

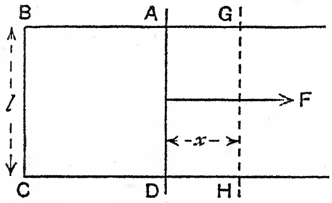


FIG. 172.

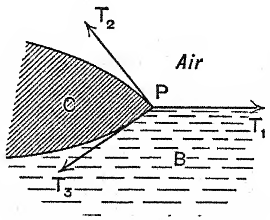


FIG. 173.—ANGLE OF CONTACT.

Angle of contact.—If two liquids are brought into contact as at P (Fig. 173), both being in contact with air, there are three surface tensions to consider, namely, T_1, that of the surface between air and liquid B; T_2, that between air and liquid C; and T_3, that between liquid B and liquid C. If the figure is a section at right angles to the line of contact, a fine wire along the line of contact at P would have

three forces acting upon it, T_1, T_2 and T_3 dynes per unit length. If a triangle of forces can be constructed, its sides will give the directions of T_1, T_2 and T_3 for equilibrium. This triangle of forces is known as **Neumann's triangle.** There are no two pure liquids known for which it is possible to construct the triangle of forces. One of the three surface tensions is always greater than the other two, so that there is no equilibrium like that shown in the diagram. The lighter liquid thus spreads over the surface of the liquid on which it rests. Thus a drop of pure water placed on the surface of pure mercury spreads over it, forming a uniform thin layer, the surface tension of mercury being about 550 dyne cm.$^{-1}$, and of water 75 dyne cm.$^{-1}$. If, however, the surface of the mercury is contaminated with grease, it is possible for drops of water to stand upon it; the surface tension of the mercury is lowered and it is possible to construct Neumann's triangle.

A more important case is that of a liquid in contact with a solid. There is no reason to suppose that the act of solidification destroys surface tension, and the arguments used in the explanation of the surface tension of liquids (p. 250) are just as valid for the case of a solid, although the result of it may not be seen, on account of the rigidity of the solid. If a drop of molten glass is allowed to solidify, it undoubtedly has surface tension before solidification, because it assumes a spherical shape. As surface tension always decreases with rise of temperature, or increases with fall of temperature, it is natural to suppose that the surface tension of the solid may be even greater than that of the molten glass.

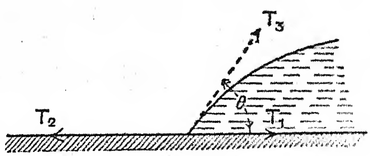


FIG. 174.—ANGLE OF CONTACT.

In Fig. 174 let T_2, T_3 and T_1 be the surface tensions for air-solid, air-liquid and liquid-solid respectively. Then if $T_2 > T_1 + T_3$, there cannot be equilibrium and the liquid spreads over the solid. If, however, there is equilibrium, $T_2 = T_1 + T_3 \cos\theta$, where θ is the **angle of contact** of the liquid with the solid,

$$\cos\theta = \frac{T_2 - T_1}{T_3}.$$

If $T_2 > T_1$, $\cos\theta$ is positive and θ is less than 90°. If $T_1 > T_2$, $\cos\theta$ is negative and θ lies between 90° and 180°. This is the case with mercury on glass, where θ is about 140°. For water and many liquids that wet glass, the angle of contact is 0°.

Measurement of angle of contact.—In the case of mercury and glass the angle of contact may be found by sloping the glass in such a way that the surface of the mercury is plane, right up to the glass. A spherical bulb (Fig. 175) is nearly filled with clean mercury, and the level of mercury adjusted until there is no meniscus or curved portion where the mercury meets the glass. This may be tested by observing the image of a bright light produced by the surface of the mercury. A bright band near the point of contact indicates that the surface is still curved. If the diameter of the circle AB is measured with a pair of calipers, and also the diameter of the bulb, $AC = \frac{1}{2}AB$ and $OA = \frac{1}{2}$ (diameter of bulb). If the bulb consists of a thin layer of blown glass, the error in taking outside measurements is not great. Then $\cos OAC = \frac{AC}{OA}$, from which angle OAC may be found, and the angle of contact DAC is $(90° + \widehat{OAC})$.

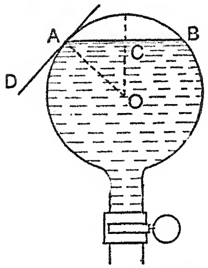


FIG. 175.—MEASUREMENT OF ANGLE OF CONTACT.

An alternative method consists of dipping a strip of plane glass into mercury, as shown in section in Fig. 176, until the mercury

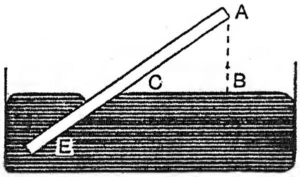


FIG. 176.—MEASUREMENT OF ANGLE OF CONTACT.

meets the glass at C without curvature. Then if a plumb line AB is dropped from A, AB and BC may be measured. Then

$$\tan ACB = \frac{AB}{BC},$$

and the angle of contact ECB is $(\pi - \widehat{ACB})$.

Pressure, curvature and surface tension.—Whenever the surface of a liquid is curved, there results from surface tension an inward pressure, which, if the surface is at rest, must be balanced by an equal

pressure acting outwards. Let ABCD (Fig. 177) be a surface, curved in one direction only, that is, part of a cylindrical surface. The surface tension is a force acting across every unit length of the boundary. The forces over AD and BC are equal and opposite, and therefore have zero resultant. The forces over AB and DC, however, are not opposite, but have a resultant perpendicular to the surface. In order to find this resultant, consider a small piece of the surface,

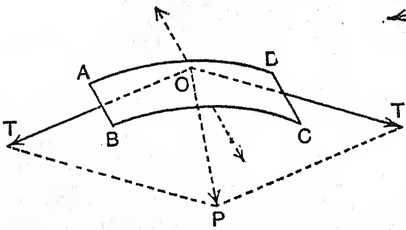


FIG. 177.—CYLINDRICAL SURFACE.

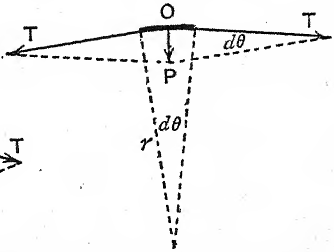


FIG. 178.—PRESSURE DUE TO CURVATURE.

of unit length in the direction AB. The force at each end is T dynes. If these forces meet at O (Fig. 178), the resultant OP is $T\,d\theta$. Now the area of the element of surface is $1 \times r\,d\theta$, and a resultant pressure p on this area gives rise to a force $pr\,d\theta$ directed outwards. If then

$$pr\,d\theta = T\,d\theta,$$

the element is at rest under the action of these two forces;

$$\therefore\ p = \frac{T}{r} \text{ dyne cm.}^{-2}.$$

This resultant pressure is the difference of pressure on the two sides of the surface that is required to balance the effect of surface tension. The pressure must be greater on the concave side of the surface than on the convex side, for the resultant to be directed outwards and so balance the force due to surface tension.

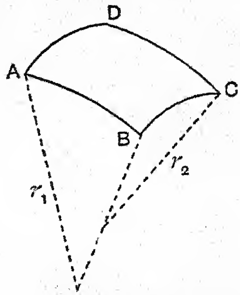


FIG. 179.—SURFACE CURVED IN TWO DIRECTIONS.

In the same manner, it may be found, if the film is curved at right angles to the first direction, that there is a similar pressure due to this second curvature. If then the film is curved in two directions at right angles to each other, as in Fig. 179, the pressure due to the

curvature of AB and DC is $\frac{T}{r_1}$, and that due to the curvature of AD and BC is $\frac{T}{r_2}$, so that the total difference of pressure p between the two sides of the film is given by

$$p=\frac{T}{r_1}+\frac{T}{r_2}$$
$$=T\left(\frac{1}{r_1}+\frac{1}{r_2}\right).$$

If the surface is spherical, $r_1=r_2=r$, and

$$p=\frac{2T}{r}.$$

In the case of a spherical soap bubble there are two surfaces, an inner and an outer, and as the film is always extremely thin, the radii of curvature are practically the same. Each surface contributes a difference of pressure $\frac{2T}{r}$ between the inside and the outside, so that in this case $p=\frac{4T}{r}$. In the case of a drop of liquid there is difficulty in measuring the pressure inside, but for a bubble there is no difficulty, as the inside is occupied by a gas or air.

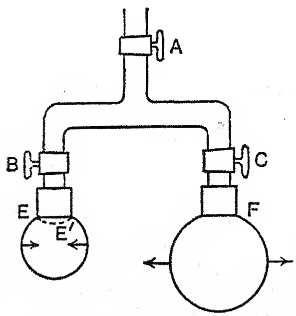


FIG. 180.—EXPERIMENT TO ILLUSTRATE THE DEPENDENCE OF PRESSURE UPON RADIUS OF A SOAP BUBBLE.

It will be noticed that the smaller the radius of the bubble, the greater is the pressure inside required to maintain it in equilibrium. This may be illustrated by a simple experiment. Two tubes with equal circular apertures E and F (Fig. 180) are dipped into a soap solution so that films are formed at E and F. On closing tap C and opening taps A and B, a bubble may be blown on E. Now closing B and opening C, a bubble is blown on F, as nearly equal in size to the bubble on E as the eye can judge. On closing A and opening B and C, the two bubbles are put into internal communication. Although they are apparently of the same size and the pressure in them would be expected to be the same, this apparent equilibrium is unstable. Whichever bubble has the smaller radius has the greater pressure, so that air will pass through B and C from the smaller to the larger bubble. Thus the smaller

bubble shrinks and the larger one is blown out. But at a certain stage the bubble, say E, becomes a hemisphere, and any further shrinkage means an increase of radius of curvature. Stable equilibrium is reached when the curvature at E′ is the same as the curvature of the bubble at F.

Measurement of surface tension of bubble.—If a bubble be blown at the end of a tube, the excess pressure can be measured by means of a manometer. The bubble D (Fig. 181) is blown with the tap A open. A is then closed and the diameter of the bubble is measured by means of a travelling microscope. The same microscope may be placed so that it can be used to measure the difference of level of the limbs B and C of the manometer. If h is this difference of level, and r the radius of the bubble, $h\rho g = \frac{4T}{r}$, where ρ is the density of the liquid of the manometer. The success of the measurement depends upon having a small bubble, and therefore a small diameter of the tube at D, so that the difference of level between B and C may be considerable.

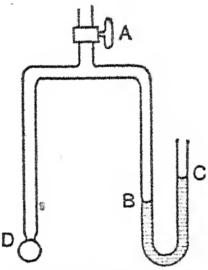


FIG. 181.—SURFACE TENSION OF BUBBLE.

Rise of liquid in a capillary tube.—One of the most important and striking effects of surface tension is the rise of liquid in a capillary tube. A capillary tube is one having a fine bore, and is so named from the Latin word *capillus*, a hair. On this account surface tension is sometimes called **capillarity.**

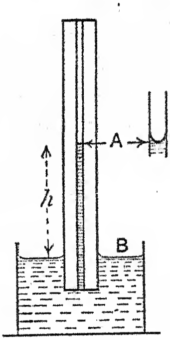


FIG. 182.—MEASUREMENT OF SURFACE TENSION BY MEANS OF CAPILLARY TUBE.

When the lower end of a capillary tube is dipped into a liquid such as water, there is an immediate rise of liquid in the tube. If the liquid wets the tube, its angle of contact can be taken to be zero, and in the case of a very fine tube the shape of the meniscus at A (Fig. 182) may be taken to be spherical. If r is the radius of the tube at A and T the surface tension of the liquid, then the difference of pressure on the two sides of the surface is

$\frac{2T}{r}$. But the pressure of the air at A and in the liquid at level B is atmospheric. Therefore, for equilibrium, the pressure $\frac{2T}{r}$ is equal to that of the column of liquid of height h;

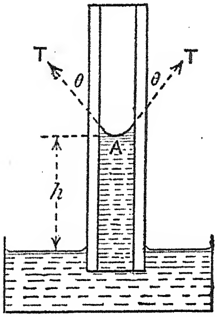


FIG. 183.—ASCENT OF LIQUID IN MODERATELY WIDE TUBE.

$$\therefore \frac{2T}{r} = h\rho g,$$

$$T = \frac{h\rho g r}{2}.$$

If the tube is not very narrow and the angle of contact is not zero, the direction of the surface tension makes an angle θ (Fig. 183) with the wall of the tube. The vertical component of this is $T \cos \theta$, and the total upward force due to it is $T \cos \theta \,.\, 2\pi r$. This force supports the column h of liquid, where h is measured from the horizontal surface of liquid outside the tube to the bottom of the meniscus at A. There is also a small volume v to be taken into account, which is the volume of liquid in the meniscus itself.

$$\therefore \text{ Total volume raised} = \pi r^2 h + v,$$

$$\text{total weight raised} = (\pi r^2 h + v)\rho g \text{ dynes};$$

$$\therefore T \cos \theta \,.\, 2\pi r = (\pi r^2 h + v)\rho g,$$

$$T = \left(\frac{\pi r^2 h + v}{\cos \theta \,.\, 2\pi r}\right)\rho g.$$

If v is negligible in comparison with $\pi r^2 h$,

$$T = \frac{r h \rho g}{2 \cos \theta}.$$

Or, as a next approximation, if the meniscus is assumed to be spherical,

$$v = \pi r^2 \,.\, r - \tfrac{2}{3}\pi r^3$$

$$= \pi r^3 - \tfrac{2}{3}\pi r^3 = \tfrac{1}{3}\pi r^3,$$

and

$$\pi r^2 h + v = \pi r^2 h + \tfrac{1}{3}\pi r^3$$

$$= \pi r^2 (h + \tfrac{1}{3} r).$$

That is, the effective height is $h+\frac{1}{3}r$.

$$T=\frac{\pi r^2(h+\frac{1}{3}r)}{\cos\theta\,.\,2\pi r}\rho g$$
$$=\frac{r(h+\frac{1}{3}r)\rho g}{2\cos\theta}.$$

If in addition $\theta=0$, as it is for most liquids examined,

$$T=\frac{r(h+\frac{1}{3}r)\rho g}{2}\text{ dynes cm.}^{-1}.$$

Measurement of surface tension by capillary tube.—In making a measurement by means of a capillary tube, the radius of the tube should be measured by placing a thread of mercury in it and measuring its length in various parts of the tube. If the length varies much, the tube should be rejected, but if the measurements agree fairly well, the mean should be taken. The weight of the mercury is found, and from this in turn the volume, the area of cross-section and the radius. Immediately before the surface tension measurements are made, the tube should be cleaned with strong soda, followed by concentrated nitric acid, and finally washed with distilled water. If it is to be used with water, it may now be placed in position, but if with any other liquid, it must be dried.

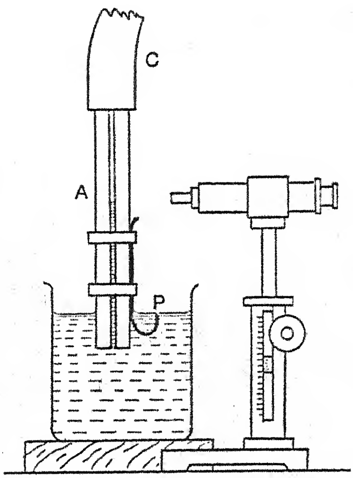


FIG. 184.—APPARATUS FOR MEASURING SURFACE TENSION BY CAPILLARY TUBE.

In order to find the capillary rise it is advisable to attach a bent pin to the tube by rubber bands so that the point of the pin may be adjusted to touch the liquid surface at P (Fig. 184). After focussing the vernier microscope on the meniscus of the liquid in the tube at A, the beaker of liquid can be taken away and the microscope lowered and focussed on P. The difference in the vernier readings gives the required height h for calculating the surface tension. The density of the liquid must be found by a separate experiment.

In measuring h a difficulty arises through the unavoidable minute contamination of the tube and the liquid, particularly in the case of

water. If the india-rubber tube C, which is open at the top, be pinched with the fingers in an appropriate manner, the liquid can be drawn up above A in the capillary tube. On releasing C, the liquid drops suddenly and stops in a definite position. It is this position that should be used in the measurement of surface tension. If the surface be watched, it will, in the case of water, be seen to creep to a position considerably below the first. This is due to contamination mentioned above causing the angle of contact to depart from zero, and the surface tension to drop. In the case of ether, benzene or petroleum, there is no such creep. The meniscus drops to a certain position and will stay there indefinitely. The reason for this seems to be that the liquid dissolves any greasy contamination from the surface of the glass.

Surface tension and temperature.—Surface tension depends upon temperature; it always decreases with rise of temperature, with the two exceptions of molten cadmium and copper. The critical temperature of a substance is the temperature at which its surface tension disappears. It is therefore important to record the temperature when making a determination of surface tension.

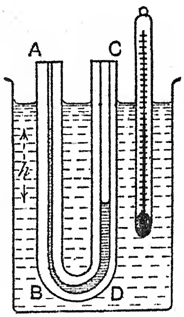


FIG. 185.—APPARATUS FOR FINDING THE RELATION BETWEEN SURFACE TENSION AND TEMPERATURE.

The apparatus of Fig. 184 is only applicable for a small range of temperature, but the method may be modified to give readings over a larger range. A fine bore tube AB (Fig. 185) is joined to a tube CD, whose bore is not so fine as that of AB. If r_1 is the radius of bore of AB and r_2 that of CD, the pressure just under the surface of liquid in AB is $\frac{2T}{r_1}$ below the atmospheric pressure. In CD it is $\frac{2T}{r_2}$. Therefore the difference of pressure in AB and CD is $2T\left(\frac{1}{r_1}-\frac{1}{r_2}\right)$;

$$\therefore\ 2T\left(\frac{1}{r_1}-\frac{1}{r_2}\right)=h\rho g,$$

or

$$T=\frac{h\rho g}{2\left(\frac{1}{r_1}-\frac{1}{r_2}\right)}.$$

The value of T should be found for many temperatures and the values plotted against $t°$.

The method of the double tube may be used to measure the surface tension of mercury, but in this case the depression is in the smaller tube, because the meniscus of mercury is convex upwards.

Then
$$\frac{2T\cos\theta}{r_1}-\frac{2T\cos\theta}{r_2}=h\rho g,$$
$$T=\frac{h\rho g}{2\left(\frac{1}{r_1}-\frac{1}{r_2}\right)\cos\theta},$$

where θ is the angle the surface of the liquid makes with the glass or the supplement of the angle of contact (p. 254).

Example.—Find an expression for the difference of pressure between the inside and the outside of a spherical air bubble of radius r in a liquid of surface tension T.

A U-tube, whose ends are open and whose limbs are vertical, contains oil of a specific gravity 0·85 and surface tension 28 dynes per cm. If one limb has a diameter of 2·2 mm. and the other a diameter of 0·8 mm., what is the difference in level of the oil in the two limbs? (Assume that the angle of contact between the oil and the glass is zero.) C.H S.C.

For the first part, see p. 256.

For the second part, refer to Fig. 185.

Difference of pressure under liquid surface in the two limbs is

$$\frac{2T}{r_1}-\frac{2T}{r_2}=\frac{2\times 28}{0\cdot 04}-\frac{2\times 28}{0\cdot 11}$$
$$=1400-509=891 \text{ dynes};$$
$$\therefore\ h\rho g=891 \text{ dynes}.$$
$$h(0\cdot 85)981=891,$$
$$\underline{h=1\cdot 07 \text{ cm.}}$$

Ferguson's method of measuring surface tension.—An important modification of the capillary tube method was made by Ferguson. One of the chief objections to the original method is that a considerable quantity of the liquid is required. In this method a small quantity of the liquid is introduced into the capillary tube AB (Fig. 186). If the liquid wets the capillary tube, the upper and lower surfaces A and B would be curved in a concave manner. Air is forced in through E until the lower surface at B is accurately plane. An electric lamp is placed obliquely at a distance of 30 or 40 cm.

and illuminates the surface at B. This is examined through a lens L, aided by an inclined mirror, and appears uniformly illuminated when the surface is accurately plane. Otherwise an image of the lamp is seen, which broadens out into a pool of light as the plane condition is attained. The method is very sensitive, and enables the balance to be made very accurately. Since the liquid surface at B is plane, surface tension does not produce any difference of pressure

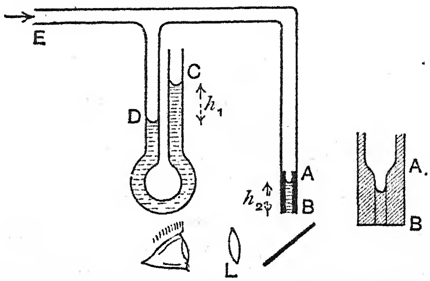


FIG. 186.—SURFACE TENSION BY FERGUSON'S METHOD.

on its two sides. Since the pressure at C is atmospheric (P), that of the air inside the tubes is $P+h_1\rho_1 g$, where ρ_1 is the density of liquid in the gauge CD. If R is the maximum radius of curvature of the meniscus at A, $\frac{2T}{R}$ is a step down in pressure in passing through the liquid surface. There is an increase in pressure due to the column of liquid h_2 in AB equal to $h_2\rho_2 g$ when the atmospheric pressure is again reached;

$$\therefore \; h_1\rho_1 g - \frac{2T}{R} + h_2\rho_2 g = 0;$$

$$\therefore \; T = \frac{Rg}{2}(h_1\rho_1 + h_2\rho_2).$$

If the radius of the tube is small and the angle of contact is zero, $R=r$, where r is the radius of the tube;

$$\therefore \; T = \frac{rg}{2}(h_1\rho_1 + h_2\rho_2).$$

If the last conditions are not fulfilled, it is still possible to make a correction for them.

The method was later modified in such a manner that it is not necessary to know the density ρ_2 of the liquid under test. This was

done by placing the tube AB horizontally, as in Fig. 187. Since the column AB does not in this case exert any hydrostatic pressure, the equation of pressure becomes

$$h_1\rho_1 g = \frac{2T}{R},$$

or with the same approximations as before,

$$T = \frac{h_1\rho_1 r g}{2}.$$

Precautions were taken to see that the film at B is not, when in the vertical position, distorted by gravitational effects, and it was

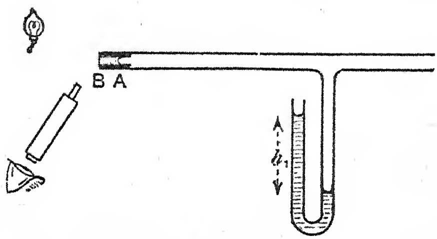


FIG. 187.—FERGUSON'S METHOD WITH HORIZONTAL TUBE.

found that with tubes less than 1 mm. in bore this distortion effect is negligible.

Jaeger's method.—It was seen on p. 256 that the pressure inside a spherical bubble in a liquid exceeds the pressure outside by the quantity $\frac{2T}{r}$. If a tube has a small aperture A (Fig. 188) at a depth

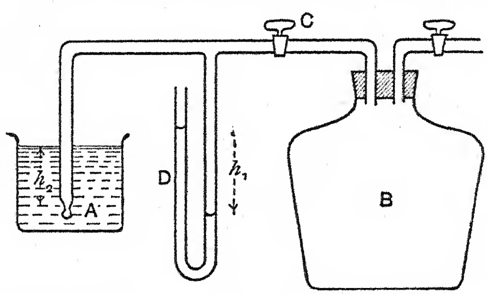


FIG. 188.—JAEGER'S METHOD OF MEASURING SURFACE TENSION.

h_2 below the surface of a liquid of density ρ_2, and an air bubble is formed at A, the air pressure inside the bubble must be in excess of

the atmospheric pressure by an amount $h_2\rho_2 g + \frac{2T}{r}$ for the bubble to grow. This excess pressure may be applied by an air reservoir B and measured by the manometer D. On opening the tap C slightly, the pressure in the tube grows slowly, and when the liquid is forced down to A, a bubble will begin to form. At first the radius of curvature diminishes, but reaches a minimum when the bubble is hemispherical (p. 257), its radius then being equal to the radius of the tube r.

Then
$$h_2\rho_2 g + \frac{2T}{r} = h_1\rho_1 g,$$
$$T = \frac{rg}{2}(h_1\rho_1 - h_2\rho_2).$$

At this point the bubble becomes unstable, because any growth causes the pressure inside it due to surface tension to become less. It therefore grows and breaks away, and the whole process begins again. The value of h_1 in the equation is the greatest value, and is reached just before the bubble breaks away.

The method does not give very accurate absolute values for the surface tension, because the phenomenon is not entirely statical, and there is an uncertainty in the exact value of the radius of the bubble when it breaks away. It is, however, useful for the comparison of surface tensions, particularly for a liquid at various temperatures, for it is easy to measure the temperature of the bath.

Drop-weight method.—When a drop of liquid is on the point of becoming detached from the bottom of a vertical circular tube, a simple consideration shows that until instability is passed, the vertical forces on the drop must balance. These forces are mg downwards, where m is the mass of the drop ; $2\pi rT$ upwards, where T is the surface tension and r the radius of the cylindrical part which is supposed to be at the aperture of the tube ; $\pi r^2 P_1$ upwards, where P_1 is the atmospheric pressure and $\pi r^2 P_2$ downwards, where P_2 is the pressure of the liquid in the plane of the orifice.

$$\therefore\ 2\pi rT = mg + \pi r^2 P_2 - \pi r^2 P_1$$
$$= mg + \pi r^2(P_2 - P_1).$$

Now
$$P_2 - P_1 = \frac{T}{r} \quad \text{(p. 255)};$$
$$\therefore\ 2\pi rT = mg + \pi rT,$$
$$T = \frac{mg}{\pi r}.$$

An examination of Fig. 198 will show that no such simple relation is valid, for the radius of the neck when the drop falls, and the amount of the drop detached, are both uncertain quantities.

By using liquids of known surface tension, Harkins and Brown have shown that the relation $T=\frac{mg}{r}F$ holds good, where F is related to V/r^3, V being the volume of the drop and r the radius of the tube. The relation between F and V/r^3 is given by means of a table.

V/r^3	F	V/r^3	F
0·8	0·255	4·0	0·256
1·0	0·261	5·0	0·253
2·0	0·264	6·0	0·249
3·0	0·260	10·0	0·261

Outside these limits the relation is complicated. In making measurements, the drops must be allowed to form very slowly, when an accuracy of 0·2 per cent. may be attained.

EXAMPLE.—Describe the most accurate method you know of measuring the surface tension of water.

Water from a depth of 4 cm. drips into the carbide chamber of a bicycle lamp through a nozzle 0·5 mm. in diameter. Show that the lamp can produce intermittently a gas pressure equal to a 10 cm. head of water without blowing back. The surface tension of water is 75 dynes per cm.

C.W.B.H.S.C.

If the water drips from the nozzle of 0·5 mm. diameter, the gas pressure below the nozzle must be less than a certain amount. If this gas pressure rises, the water will be driven back to the top of the nozzle, where it forms a hemispherical bubble of radius 0·25 mm. $=0{\cdot}025$ cm. Any greater pressure than this will cause the bubble to grow and blow back.

$$\text{Downward pressure in bubble}=\frac{2T}{r}=\frac{2\times 75}{0{\cdot}025}$$
$$=6000 \text{ dyne cm.}^{-2}$$
$$=\frac{6000}{981} \text{ cm. of water column}$$
$$=\underline{\underline{6{\cdot}1 \text{ cm. of water column.}}}$$

Therefore together with a head of 4 cm. of water, the downward pressure is equivalent to a head of 10·1 cm. of water. As the gas pressure in the lamp never exceeds a head of 10 cm. of water, it will not blow back.

Large drop on horizontal plate.—When a quantity of liquid rests upon a horizontal solid plate, which it does not wet, the shape of the drop is determined by surface tension and gravity. For extremely small drops the surface tension effects are great and the gravitational effects small, so that the former determine the shape of the drop. It is therefore spherical, as may be seen by placing minute drops of mercury upon a glass plate or water upon paraffin wax.

On increasing the size of the drop, the effect of gravitation becomes greater and that of surface tension less. Now the effect of gravitation alone would be to make the drop spread out until its surface is horizontal (p. 156). Therefore as the drop grows it becomes flattened. There is a limit to this process, which is reached when the upper surface becomes horizontal. Taking this fact in conjunction with our knowledge of the angle of contact of mercury with glass (p. 254), it follows that the shape of a very large drop of mercury upon glass is as shown in Fig. 189. The angle θ is about 40°, and the central part AB of the upper surface is plane. The shape at the edges of the drop will not concern us here, except to notice that at some level such as C the surface is vertical.

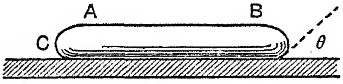


FIG. 189.—LARGE DROP OF MERCURY ON GLASS.

Consider the forces acting over the boundaries of a thin slice of the drop such as ABHG (Fig. 190), of horizontal width dl and having parallel vertical faces. The forces over the side ABHG and the back face are, from symmetry, equal and opposite. Now consider the part of the drop that lies above the horizontal plane CDF, which passes through the point C where the surface of the drop is vertical. Taking the horizontal forces in the direction AB or CD, the force due to surface tension at C is vertical, and consequently has no horizontal component. At the end BD, the only horizontal forces are the hydrostatic pressure over the face BDFE due to the liquid in the

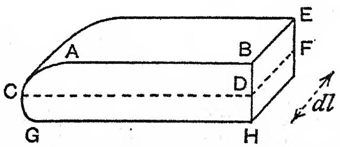


FIG. 190.—FORCES ON LARGE DROP.

neighbouring part, and the surface tension pull over BE. The hydrostatic thrust over BDFE is

$$BD \times BE \times \rho g \times (\tfrac{1}{2}BD) \text{ dynes} = h \,.\, dl \,.\, \rho g \,.\, \frac{h}{2}. \quad \text{(p. 159).}$$

$$= \frac{h^2 \rho g \, dl}{2},$$

where h is the depth BD or EF and ρ is the density of the mercury. The surface tension pull over BE is $T\,dl$;

$$\therefore \; T\,dl = \frac{h^2 \rho g \, dl}{2},$$

$$T = \frac{h^2 \rho g}{2}.$$

If the whole thickness of the bubble had been taken into account instead of the upper part alone, the hydrostatic thrust over the end EH is $\dfrac{g\rho h_1{}^2 dl}{2}$, where h_1 is BH the total thickness of the drop; the surface tension pull on BE is $T\,dl$ as before, and the horizontal pull at G is $T\,dl \cos\theta$, where θ is the supplement of the angle of contact, about 140° for mercury on glass.

$$\frac{g\rho h_1{}^2\,dl}{2} = T\,dl - T\,dl\cos\theta,$$

$$= T\,dl(1 - \cos\delta),$$

or $$T = \frac{g\rho h_1{}^2}{2(1-\cos\theta)}.$$

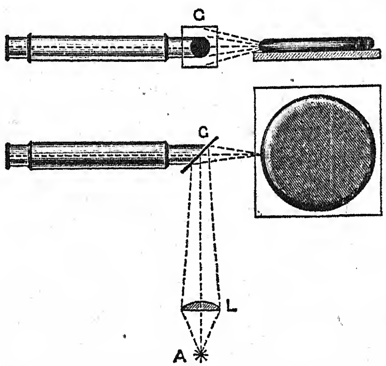


FIG. 191.—EDSER'S METHOD FOR MERCURY DROP.

This affords an alternative method of finding T when the angle of contact θ is known. Or, if T is determined by the first part, θ may be calculated from the second.

The thickness of the whole drop may be measured by means of the vernier microscope, but there is some difficulty in finding the thickness BD of the upper part, because of the uncertainty in finding the location of C, the place where the surface is vertical.

This difficulty was got over by Edser as follows. The objective of the vernier microscope is provided with a piece of plain glass G (Fig. 191), and light from an incandescent lamp A is focussed by the

lens L and the plain glass G acting as a mirror upon the edge of the drop. The light is reflected and, the plain glass being unsilvered, part passes through it and enters the microscope. On focussing the microscope, a thin bright horizontal line is seen at C where the surface is vertical. The microscope is raised or lowered until this line coincides with the cross wire in the field of vision, and the vernier reading is noted. The microscope is then raised by its screw and moved forwards until the image of the flat top of the bubble is on the cross wire. This is facilitated by scattering some fine dust such as lycopodium powder on the flat top of the bubble. The vertical travel of the microscope is the height BD or h. The whole height h_1 may be found, either by means of a spherometer, or by the vernier microscope, focussing first on the top and then on the bottom of the drop.

Cylindrical film.—On blowing a spherical soap bubble and placing it on a wire ring, and bringing another ring in contact with it, a cylindrical soap film may be formed. The film may have a variety of shapes, according to the distance apart of the rings. A distance may be found for which the film A between the rings is cylindrical, as in Fig. 192; the film B on each ring is, of course, part of a sphere. The air pressure inside the bubble is the same at every point, so that if p is the excess pressure of air inside over air outside and r is the radius of each wire ring, then for the cylindrical film, $p=\frac{2T}{r}$, since there are two surfaces to the film, and a cylinder is only curved in one direction; it is not curved in a plane which contains the axis.

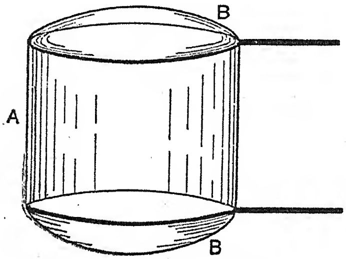


FIG. 192.—CYLINDRICAL SOAP BUBBLE.

For the spherical portion B, $p=\frac{4T}{r_1}$;

$$\therefore \quad \frac{2T}{r}=\frac{4T}{r_1},$$

or
$$r_1=2r.$$

Thus for the same excess pressure, the spherical film must have twice the radius of curvature of the cylindrical film.

If the rings are drawn apart, the value of p is reduced. Thus the radius r_1 is increased, and the films B flatten. This reduced pressure means that the cylinder is drawn in, so that r becomes r_2 (Fig. 193).

This in itself would mean an increased pressure inside, but the surface is now curved longitudinally with the centre of curvature *outside* the film. Thus the two radii of curvature r_2 and r_3 are oppositely directed, and $p=\frac{2T}{r_2}-\frac{2T}{r_3}$. A surface having curvatures in opposite directions is called an **anti-clastic surface.**

If the separation of the rings is continued until the portions B are plane, the pressure inside is the same as that outside, that is,

$$p=0 \quad \text{and} \quad \frac{2T}{r_2}-\frac{2T}{r_3}=0;$$

$$\therefore\ r_2=r_3.$$

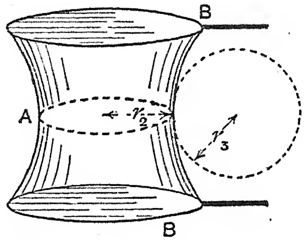


FIG. 193.—FILM WITH OPPOSITELY DIRECTED CURVATURES.

Thus it is possible to have a curved film with the gas pressure the same on both sides of it, and if the plane films B are destroyed, the film A will not be affected. On moving the rings still further apart without destroying B, the pressure may be lowered below that of the atmosphere, but as the neck at A gets narrow, the film becomes unstable, as will be seen later, and it breaks into two separate bubbles.

Stability of cylindrical film.—By means of two rings A and B (Fig. 194) a cylindrical soap film may be formed. By means of the tap

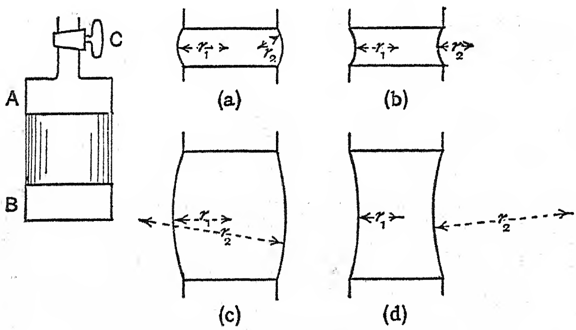


FIG. 194.—STABILITY OF SOAP BUBBLE.

C the interior of the film may be cut off from the atmosphere, or air may be blown in or drawn out, so that the relation between the pressure and the dimensions of the film may be studied.

If the cylinder is short, as at (*a*), an increase of pressure p blows it out, and both r_1 and r_2 are directed inwards. If the tap C is opened so that $p=0$, the film moves inwards, and r_2 is directed outwards as at (*b*). But r_2 changes much more rapidly than r_1, so that the condition $r_2=r_1$ is soon reached, and the film is in stable equilibrium.

If, however, AB is large ($r_2>r_1$), an increase in p produces a bulging as in (*c*), and on opening C as in (*d*), r_2 becomes negative. But for a given movement of the film r_1 changes more rapidly than r_2. The curvature corresponding to r_1 produces an inward force due to surface tension and r_2 an outward force, and as the former increases more rapidly than the latter, the inward force will always predominate, and by a greater and greater amount as the film moves in, so that there is instability and the film collapses.

There is consequently some limiting length of cylinder, which separates the unstable from the stable film. This limiting length is πr, or a length equal to half the circumference of the

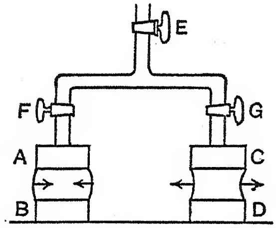


FIG. 195.—SHORT CYLINDRICAL SOAP BUBBLE.

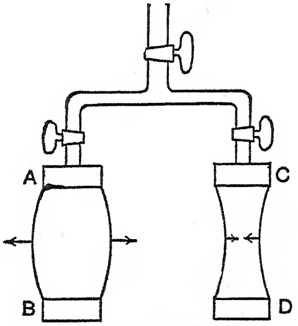


FIG. 196.—LONG CYLINDRICAL SOAP BUBBLE.

cylinder. This may be illustrated by an experiment similar to that described on p. 256. Cylindrical soap films are blown between circular supports AB and CD (Fig. 195). AB is given a slight extra pressure so that it bulges outwards, and CD a less pressure so that it bulges inwards, and then with the tap E closed, F and G are opened so that the air inside the films can come to the same pressure. Provided that AB is less than half the circumference of the ring A, air will pass from AB to CD until the two bubbles come to the same shape. But if AB is greater than half the circumference of ring A (Fig. 196), a similar experiment will have a different result. The

air pressure in CD is greater than in AB, and on putting the two in communication, air will pass from CD to AB. CD will therefore shrink and AB will grow, until the walls of CD meet and the bubble breaks up.

If we imagine the bubbles AB and CD joined end to end to form one long cylindrical bubble, the state of affairs in the last experiment is repeated. AB and CD (Fig. 197) are the two halves of the bubble, whose length AD is greater than the circumference of the cylinder. The bubble is unstable, because any slight disturbance which makes, say, CD shrink brings into play pressures which will cause CD to shrink further, by forcing air from CD to AB. This ends with CD collapsing and forming a large spherical bubble at A and a small one at D.

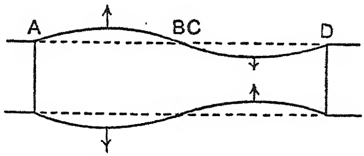


FIG. 197.—INSTABILITY OF LONG CYLINDRICAL BUBBLE.

This instability of a cylindrical film may be seen if it is attempted to wet a small wire throughout its length. The water will gather into globules at regular intervals.

As a rule the breaking up of a cylinder of liquid is too rapid to follow by eye, but if the process is made to go slower by using a viscous liquid, it may be watched. A fine thread of treacle will remain for some time owing to its great viscosity, but it will be seen that it breaks up eventually into drops.

If a tube A (Fig. 198) contains carbon disulphide, and this be allowed to flow very slowly into a beaker of water, the formation of the drop may be watched. The stages B, C, D, E and F can be seen. At E a very narrow neck is developed, and as this elongates it becomes unstable as described above, and breaks up, leaving a very small drop P, known as **Plateau's spherule.**

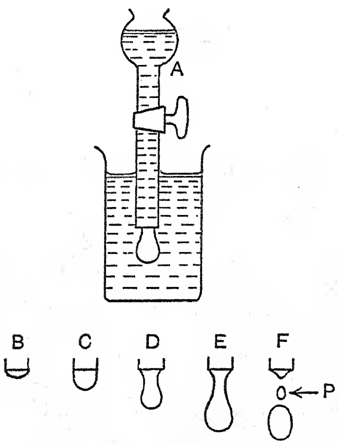


FIG. 198.—FORMATION OF DROPS.

Drop between plates.—If two clean pieces of plate glass are put face to face, there is no difficulty in separating them. But if there is a small drop of water between them, which is squeezed into a thin

layer, it requires a considerable force to pull the plates apart. The reason is that the surface tension at the outer edge of the film of water causes a difference of pressure $\frac{2T}{d}$ between the water and the outer air, where d is the distance between the plates (Fig. 199). If

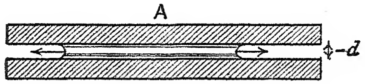


FIG. 199.—DROP BETWEEN PLATES.

A is the area of the film, the total force pushing the plates together is due to the excess of atmospheric pressure outside the plates over the liquid pressure between them, acting over the area A. Thus,

$$\text{force} = \frac{2TA}{d}.$$

This force presses the plates together, making d small and A large. The curvature of the water surface parallel to the plane of the plates is so slight that its effect may be neglected in comparison with the very great curvature $\frac{2}{d}$ at right angles to them. Also, if the glass surfaces are not quite plane, they may touch at some places before d becomes very small. The force urging the plates together will then not be very great.

EXAMPLE.—Two glass plates are separated by water. If the area of each plate wetted is 8 sq. cm. and the distance between the plates is 0·0012 mm., what is the force urging the plates together? ($T = 75$ dyne cm.$^{-1}$.)

$$\begin{aligned} \text{Force} &= \frac{2TA}{d} \\ &= \frac{2 \times 75 \times 8}{0{\cdot}00012} \text{ dynes} \\ &= \underline{\underline{10^7 \text{ dynes.}}} \end{aligned}$$

That is, nearly 10 kilograms wt.

Force between bodies partly immersed in a liquid.—It is well known that light bodies such as pieces of cork, floating on water, will adhere together and collect into groups. This may be explained by the capillary rise which occurs when the space between the bodies is small.

If two glass plates are wetted by the water in which they are partially immersed (Fig. 200 (*a*)), they are pushed together. The reason is similar to that described on p. 272. On the outside, over AB and CD, the pressure is atmospheric, but inside the column of liquid the pressure is less than atmospheric. Hence over AB and CD there is a resultant force pushing the plates together.

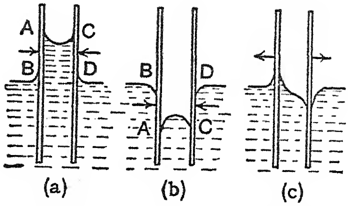


FIG. 200.—BODIES PARTLY IMMERSED.

If the liquid does not wet the plates, as in the case of glass plates partially immersed in mercury (Fig. 200 (*b*)), there is still an apparent attraction between them. Owing to the depression of the liquid between the plates, the pressure of the liquid at each point outside at AB or CD is greater than the atmospheric pressure which exists on the inside between AB and CD. Hence there is a resultant force pushing the plates together.

If, however, one plate is wetted by the liquid and the other is not (Fig. 200 (*c*)), as, for example, with a clean glass plate and one with a thin coating of paraffin wax, the plates when close together will appear to repel each other. The hydrostatic pressures will not explain this effect, and the pulls due to surface tension must be examined. In the first two cases the horizontal forces due to surface tension were the same on both sides of each plate, because there is a horizontal part of the surface of the liquid between the plates as well as outside. But in (*c*), when the plates are close together, there is no horizontal surface of liquid between them, so that the horizontal component of the surface tension between the plates is less than that outside. Hence there is a resultant force on each plate pulling them apart.

Vapour pressure and surface tension.—It was seen on p. 250 that the process of evaporation, or the escape of molecules through a liquid surface, is connected with the attraction between the molecules, as was the surface tension of the liquid. It seems reasonable then that there should be some relation between vapour pressure and surface tension. The escape of molecules from the liquid is hindered by the attraction of those beneath the surface, but the reverse process is not hindered. Every molecule in the vapour which strikes the liquid surface, enters it, so that condensation goes on at a rate which is proportional to the pressure of the vapour above the liquid. When the vapour in an enclosed space has risen to such

a value that the processes of evaporation and condensation go on at equal rates, the maximum vapour pressure is reached.

In order to find a relation between maximum vapour pressure and surface tension, consider a capillary tube AB dipping into a liquid so that the capillary rise AB is given by $T=\frac{h\rho gr}{2}$, where ρ is the density of the liquid (see p. 258). If the system is enclosed within a chamber CD (Fig. 201) which cuts it off completely, thermally as well as otherwise, from the exterior, it will settle down to a steady state. There is then a difference of vapour pressure $h\sigma g$, between the levels A and B, where σ is the density of the vapour. If p is the maximum vapour pressure at B, then that at A is $(p-h\sigma g)$, and this must be the maximum vapour pressure in contact with the curved surface of the liquid at A. If it were not, then there would be either condensation or evaporation at A and a circulation would be set up. As such a circulation would mean perpetual motion without the supply of energy from outside, and as this is contrary to experience, we must conclude that the vapour pressure $(p-h\sigma\rho)$ is the maximum for contact with the curved surface at A, where p is that for the vapour in contact with a plane surface such as B. If $h\sigma g=dp$, then since

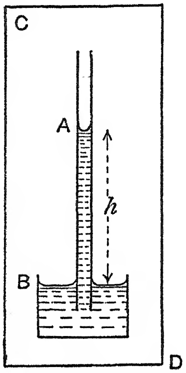


FIG. 201.—CAPILLARY TUBE IN ENCLOSURE.

$$T=\frac{h\rho gr}{2}, \quad h=\frac{2T}{\rho gr};$$

$$\therefore \ dp=\frac{2T\sigma g}{\rho gr}=\frac{2T\sigma}{\rho r},$$

It does not matter whether air is present or not, except for the small effect of the pressure of a column of air and vapour in supporting the column of liquid. But as the density of the liquid is always many times that of the gas and vapour, this small correction has been omitted.

If the vapour is treated as a gas and subject to the equation $pv=R\theta$, since $v=\frac{1}{\sigma}$, $\sigma=\frac{p}{R\theta}$;

$$\therefore \ dp=\frac{2Tp}{R\theta\rho r}.$$

Note that the absolute temperature has here been written θ, to prevent confusion with the surface tension T.

The quantity $\frac{dp}{p}$ is the relative lowering of the maximum vapour pressure.

Effect on evaporation and condensation.—It will be seen from above that when the liquid surface is concave (Fig. 201), the maximum vapour pressure is below that for a plane surface. A similar argument would show that when the meniscus is convex, the column is depressed and the maximum vapour pressure is greater than that over a plane surface.

Hence if a drop of water is in a space in which the vapour pressure is the maximum for a plane surface, the vapour pressure existing is less than that for the drop. The drop will therefore evaporate. The effect is very small for large drops, for, taking $T=75$ dyne cm.$^{-1}$, $\theta=273°$, $\rho=1$ and $\sigma=0{\cdot}61\times10^{-3}$ gm. per c.c.,

$$dp=\frac{2T\sigma}{\rho r}=\frac{2\times75\times0{\cdot}61\times10^{-3}}{1\times0{\cdot}05}\text{ dyne cm.}^{-2}$$

for a drop of 1 mm. diameter,

or $$dp=\frac{2\times75\times0{\cdot}61\times10^{-3}}{1\times0{\cdot}05\times981\times13{\cdot}6}\text{ cm. of mercury column}$$

$$=0{\cdot}000137\text{ cm. of mercury column.}$$

This is such a small amount that its effect is unimportant. But if the diameter of the drop is one-thousandth of a millimetre,

$$dp=0{\cdot}137,$$

and in the incipient stage of drop formation the diameter of the drop is nearer a millionth of a millimetre;

$$\therefore\ dp=137.$$

Of course, this result must not be taken literally, as the surface tension would certainly not remain constant for such small drops. It does show, however, that the rate of evaporation for very small drops is considerable. In fact, it seems likely that the direct formation of drops from vapour is impossible. A collection of a few molecules would exert such a small attraction on others that the collection would never grow into a drop. The fact that dust-free vapour does not form drops at a temperature far below the normal temperature of condensation is well known. A dust particle is a comparatively large body, so that condensation in a supersaturated vapour would immediately occur on the comparatively large particle, and once started, every drop so formed would grow. This

accounts for the fact that in a dust-laden atmosphere, a fall in temperature which produces supersaturation immediately causes a cloud or fog, which in a dust-free atmosphere would not be formed.

The opposite phenomenon occurs in the process of boiling, for a concave surface produces a lowering of the maximum vapour pressure. Hence it favours condensation. A liquid may be heated above the normal boiling point if free from bubbles of air, because of the difficulty in starting the bubble. But if once started, the evaporation goes on to form the bubble with explosive violence. Hence the term " bumpy " boiling for air-free water. But any porous body in the liquid, which contains minute air-bubbles, provides a bubble of suitable size, so that evaporation goes on easily and the boiling is no longer bumpy.

Surface energy and temperature coefficient of surface tension.—It is possible to find a relation between the change of surface tension with temperature and the total energy required to produce unit area of surface. For this purpose, imagine a film to be used as a reversible engine (p. 239). The efficiency of such an engine is known in terms of the absolute temperatures of the heater and cooler. The relation is

$$\frac{\text{heat converted into work in a cycle}}{\text{heat drawn from heater}} = \text{efficiency}$$

$$= \frac{\text{difference in temperatures of heater and cooler}}{\text{temperature of heater}}.$$

Consider a film to be stretched isothermally at absolute temperature θ. Mechanical work AT is required (p. 252) to perform the stretching, where A is the area of film produced, and T the surface tension. At the same time heat is supplied by the heater at temperature θ, in order to maintain the temperature of the film constant. If h is the amount of heat supplied for the formation of unit area of surface, hA is the heat given by the heater to the film to produce unit area isothermally.

When the stretching A is complete, let a very small adiabatic expansion be produced. As no heat is supplied, the temperature falls, by the small amount $d\theta$. The surface tension is now $T - \frac{dT}{d\theta}d\theta$, where $\frac{dT}{d\theta}$ is the coefficient of increase of surface tension with temperature. Let the film now contract by the amount A. Mechanical work

$$A\left(T - \frac{dT}{d\theta}d\theta\right)$$

is performed by it. A further small adiabatic contraction brings the film back to its original condition. The adiabatic changes may be made as small as we please, and the two amounts of work during them are in opposite directions, and so may be considered not to add to the total work performed. Thus the balance of work performed by the film upon external bodies is

$$A\left(T-\frac{dT}{d\theta}d\theta\right)-A\,d\theta=-A\frac{dT}{d\theta}\,d\theta.$$

The heat drawn from the source is Ah, and if this is expressed in ergs, the above efficiency equation becomes

$$\frac{-A\dfrac{dT}{d\theta}d\theta}{Ah}=\frac{d\theta}{\theta};$$

$$\therefore\ h=-\theta\frac{dT}{d\theta}.$$

The negative sign occurs because $\frac{dT}{d\theta}$ is negative for all liquids.

The total energy (E) supplied to produce unit area of film is therefore $T+h$,

or
$$E=T+h,$$
$$E=T-\theta\frac{dT}{d\theta}.$$

E is known as the **total surface energy**, and its value has been calculated, in the case of many substances, from the measured values of T and $\frac{dT}{d\theta}$.

Taking the surface tension of water at 15° C., or 288° A. as 74 dynes per cm. and $\frac{dT}{d\theta}$ as $-0{\cdot}148$,

$$E=74+(288\times0{\cdot}148)$$
$$=74+43=117 \text{ ergs per sq. cm.}$$

The total surface energy is thus much greater than the energy due to surface tension. The latter is sometimes called **free surface energy**, and is numerically equal to T (p. 252).

Internal or intrinsic pressure.—It has been seen how Laplace accounted for surface tension (p. 250) by suggesting that the molecules of a liquid attract each other. In the interior of the liquid the

forces of attraction due to surrounding molecules are arranged symmetrically in all directions, while at or near the surface, the resultant of all the attractions is directed inwards. The law of force between the molecules is not known with any certainty. It is not the ordinary law of gravitational attraction, that the force varies inversely as the square of the distance apart. It is more likely that instead of the square, it is the eighth power of the distance that determines the force, and there is a large amount of evidence that the forces are of the kind concerned with chemical combination.

Owing to these attractions, there must be a pressure in the interior of a liquid. This has been named **internal or intrinsic pressure,** and is the cause of cohesion. In liquids, the cohesive force is considerable when the liquid is in the pure state and free from minute air-bubbles, while in a gas it is exceedingly small. This pressure is the term a/v^2 (see Edser's *Heat*), which is added to the external pressure p in order to give the whole pressure in van der Waals' modification of the gas equation,

$$\left(p+\frac{a}{v^2}\right)(v-b)=RT.$$

Let us consider the attraction between a thin plane of the liquid and a small particle of mass m situated at distance r from the plane to be $mm'\psi(r)$, where m' is the mass per square centimetre of the liquid in the plane. Then, if the thickness of the plane is dr and the density of the liquid ρ,

$$m'=\rho\, dr,$$

and the attraction between the mass m and the plane is $m\rho\psi(r)\,dr$.

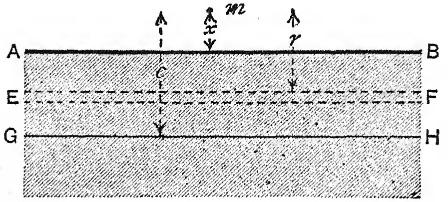


FIG. 202.—ATTRACTION OF LIQUID FOR EXTERNAL PARTICLE.

To fix our ideas, consider the mass m to be situated above the free surface of the liquid, as in Fig. 202. Then if EF is the layer of the liquid, the attraction of EF for m is $m\rho\psi(r)\,dr$. This, of course, becomes zero when the distance r is equal to the limit at which the attraction between molecules produces any effect, that is, when r equals c the range of molecular attraction (p. 250). c is very small on account of the rapid falling off of the force between molecules corresponding to the eighth power of the distance, although, on

the other hand, the force between molecules is probably very great when they are close together, if the forces are connected with chemical affinities. It must be remembered that chemical affinity is due to electric charges possessed by atoms, and these have electric and magnetic fields, to which chemical combination is due. These fields surround the molecule to some distance, and it is to these stray fields that the attraction between molecules is due. It is therefore not surprising that the attraction should fall off according to a high power law, when it is remembered that the force between two magnets, which have strong fields surrounding them, falls off inversely as the fourth power of the distance. Neither is it surprising that the effective range c should not be a constant and definite quantity for all substances.

Returning to Fig. 202, the force exerted on m by the whole liquid is the sum of the forces due to all the layers of liquid between AB and GH, where GH is at a distance c from m.

That is,
$$\text{total force} = \int_x^c m\rho\psi(r)\,dr$$
$$= m\rho\int_x^c \psi(r)\,dr.$$

The integration cannot be performed, because the form $\psi(r)$ is unknown. But if it could be performed and the limits c and x substituted for r, the result would be a function of x, c being considered constant for the given liquid. It is convenient to write

$$\int_x^c \psi(r)\,dr$$

as a function of x only; thus

$$\int_x^c \psi(r)\,dr = \phi(x).$$

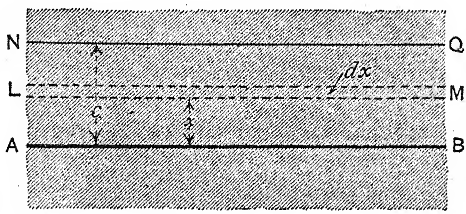


FIG. 203.—INTRINSIC PRESSURE.

This means that the attraction of the whole liquid for a point mass m situated at distance x from its plane surface is $m\rho\phi(x)$.

It is now possible to calculate the force acting across unit area of a plane in the liquid, due to molecular attractions. For, consider AB (Fig. 203) to be any plane drawn in the interior of the liquid, and let LM be a layer of liquid of thickness dx, parallel to AB. Unit area of LM contains a mass $m = \rho\,dx$ of liquid, and the attraction upon this due to all the liquid below AB is $m\rho\phi(x) = \rho^2\phi(x)\,dx$. Only that liquid

within distance c of AB experiences any sensible force due to the liquid below AB.

$\therefore$ whole force across unit area on the liquid above AB due to the liquid below AB is $\int_0^c \rho^2 \phi(x)\,dx$. This is the intrinsic pressure in the liquid, which causes cohesion. Calling it K,

$$K = \rho^2 \int_0^c \phi(x)\,dx.$$

Estimation of intrinsic pressure.—The quantity a/v^2 in van der Waals' equation affords a means of estimating intrinsic pressure, but for this the student is referred to works on Heat. A more direct method is to calculate the work done on a small quantity of the liquid in carrying it from the interior, into the free space above the liquid, where it becomes vapour. This work, together with the work done in driving back any gas or vapour present (p. 135), is the mechanical equivalent of the heat required to produce evaporation at constant temperature. This quantity is very well known, and it remains to apply our method of molecular attraction to the calculation of the amount of work required to carry a small quantity of the liquid from the interior to the free space above the surface. No work is done while the element of liquid is at a greater depth than c below the surface, as the forces due to the rest of the liquid are symmetrically distributed around it. The calculation is in two parts: (a) to find the work required to carry a small volume v of liquid from depth c to the surface, and (b) to carry the same from the surface to a distance c above it. As (b) is the simpler, it will be taken first.

(b) In Fig. 203 let a small mass m be situated in the layer LM. The force in this due to all the liquid below the surface AB is $m\rho\phi(x)$.

The work done in moving this through distance dx is $m\rho\phi(x)\,dx$, and the total work in carrying it from AB to NQ is

$$\int_0^c m\rho\phi(x)\,dx = m\rho \int_0^c \phi(x)\,dx.$$

If v is volume of the mass m of liquid,

$$m = \rho v;$$

$$\therefore \text{ work} = v\rho^2 \int_0^c \phi(x)\,dx = vK \text{ (see above).}$$

$\therefore$ work done in removing unit volume of the liquid from the surface to distance c is K. The liquid, in evaporating at the surface, does not, of course, move away in layers; it escapes molecule by molecule. But the total mechanical work done in removing a given quantity of the liquid is independent of the rate at which this takes place.

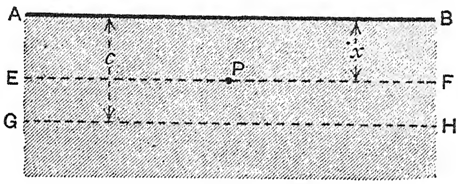


FIG. 204.—INTERIOR OF LIQUID.

(*a*) In order to find the work done in carrying the mass m from GH (Fig. 204) to the surface AB, the resultant force at each point must be found. The downward force is known: it is

$$m\rho\int_0^c \psi(r)\,dr,$$

where r is measured downwards from P (p. 278). There is also an upward force $m\rho\int_0^x \psi(r)\,dr$ due to the liquid between AB and EF. Hence the resultant downward force on m is

$$m\rho\int_0^c \psi(r)\,dr - m\rho\int_0^x \psi(r)\,dr = m\rho\int_x^c \psi(r)\,dr$$
$$= m\rho\phi(x). \quad \text{(p. 279).}$$

Work done in moving over distance $dx = m\rho\phi(x)\,dx$.

And total work done in moving from GH to AB or AB to GH is

$$\int_0^c m\rho\phi(x)\,dx = m\rho\int_0^c \phi(x)\,dx$$
$$= v\rho^2\int_0^c \phi(x)\,dx,$$

or for unit volume, $$\text{work} = \rho^2\int_0^c \phi(x)\,dx = K.$$

It follows that in order to remove unit volume from the interior of the liquid to the free space above it, the total work is $2K$, that is, it is numerically equal to twice the intrinsic pressure.

If the case of water at 15° C. is taken, $\rho = 0{\cdot}999$, and may be taken as unity. The latent heat of evaporation at 15° C. is 586 calories per gm. If the water vapour at 15° C. obeys the gas laws, its volume

per gram calculated from a vapour pressure of 1·278 cm. of mercury is 78,030 c.c. The evaporation of this volume of vapour pushes back the vapour already present, whose pressure is $\frac{1 \cdot 278}{76} \times 1 \cdot 013 \times 10^6$ dynes per sq. cm., taking the standard atmosphere as $1 \cdot 013 \times 10^6$ dynes per sq. cm. The work done, since the pressure is constant, is therefore (p. 135)

$$\text{pressure} \times \text{volume} = \frac{1 \cdot 278 \times 1 \cdot 013 \times 10^6 \times 78030}{76} \text{ ergs}$$

$$= \frac{1 \cdot 278 \times 1 \cdot 013 \times 10^6 \times 78030}{4 \cdot 182 \times 10^7 \times 76} \text{ calories}$$

$$= 31 \cdot 76 \text{ calories.}$$

$$\therefore \text{ Internal heat} = 586 \cdot 5 - 31 \cdot 76$$

$$= 554 \cdot 7 \text{ calories per gm.}$$

$$\therefore \; 2K = 554 \cdot 7 \times 4 \cdot 182 \times 10^7,$$

$$K = 554 \cdot 7 \times 2 \cdot 091 \times 10^7 = 1 \cdot 160 \times 10^{10} \text{ dynes per sq. cm.}$$

$$= \frac{554 \cdot 7 \times 2 \cdot 091 \times 10^7}{1 \cdot 013 \times 10^6} \text{ atmospheres}$$

$$= \underline{11450 \text{ atmospheres.}}$$

This is of the same order of magnitude as the result obtained by considering van der Waals' equation (p. 278), and is the value of the intrinsic pressure in the liquid. From its magnitude it is seen that cohesion must be very great. The difficulty of observing the cohesive force directly arises from the fact that impurities such as dissolved gases are present, and produce a discontinuity at which the liquid breaks on applying a tensile stress to a column of the liquid.

Estimate of range of molecular attraction.—If a liquid can be divided along a plane and the two parts pulled apart perpendicularly to this plane, two new surfaces are created. The energy required to produce unit area of new surface is equal to the surface tension T, apart from the heat required to maintain constant temperature (p. 277). As the separation produces two new surfaces, the total work done is equal to $2T$.

The work done in raising one part of fluid from the other so that AB (Fig. 203) is the plane of separation may be found by noting that

the force on mass m in the layer LM is $\rho m\phi(x)$, and the work done in moving it from distance x to distance c is

$$\int_x^c \rho m\phi(x)\,dx \quad \text{or} \quad \rho m\int_x^c \phi(x)\,dx.$$

For a moment, write p for $\int_x^c \phi(x)\,dx$. Then, work done in moving mass m from LM to NQ is ρmp. Now if m is the mass of unit area of the layer, $m=\rho\,dx$, and work $=\rho^2 p\,.\,dx$. For all the layers from AB to NQ

$$\text{total work}=\int_0^c \rho^2 p\,dx=\rho^2\int_0^c p\,.\,dx.$$

If $\int p\,dx$ is integrated by parts, it is

$$px-\int x\,.\,\frac{dp}{dx}\,dx.$$

Now $$p=\int_x^c \phi(x)\,dx\,; \quad \therefore \quad \frac{dp}{dx}=-\phi(x),$$

and $$\rho^2\int_0^c p\,dx=\Big[\rho^2 p\,.\,x\Big]_0^c-\rho^2\int_0^c x\phi(x)\,dx.$$

Since $\rho^2 p=\rho^2\int_x^c \phi(x)\,dx$, this is zero when $x=c$, and $(\rho^2 p\,.\,x)$ it is zero when $x=0$;

$$\therefore \quad \Big[\rho^2 px\Big]_0^c=0.$$

Without knowing the form of the function ϕ it is impossible to integrate $\int_0^c x\phi(x)\,dx$, but since both force and work become zero when x exceeds c, c is the greatest value of x entering into the expression for the work, so that the greatest value the expression can have is

$$\rho^2 c\int_0^c \phi(x)\,dx=cK. \quad \text{........................(p. 280)}$$

Now, putting $\rho^2\int_0^c x\phi(x)\,dx=2T$, then $\rho^2 c\int_0^c \phi(x)\,dx$, or cK must be greater than $\rho^2\int_0^c x\phi(x)\,dx$, or $2T$,

$$cK>2T \quad \text{or} \quad c>\frac{2T}{K}.$$

Taking the values $T=74$ dynes per cm. and $K=1{\cdot}16\times10^{10}$ (p. 282),

$$c > \frac{2\times 74}{1{\cdot}16\times10^{10}}$$
$$> 1{\cdot}27\times10^{-8} \text{ cm.},$$
$$> 0{\cdot}127\ \mu\mu \text{ (micro-millimetres).}$$

This gives the smallest value that c can have. It is in fair agreement with molecular distances as obtained from other experiments, which shows that the attraction between molecules does not extend to much more than the distance between adjacent molecules.

Solutions and stability of thin films.—When a substance is dissolved in a liquid, the surface tension may be increased or decreased, according to the nature of the substance. Many organic substances lower the surface tension when dissolved in water. For example, the surface tension of methyl alcohol is 23 dyne cm.$^{-1}$, and the surface tension of various solutions of alcohol and water lies between 23 and 74 dyne cm.$^{-1}$. On the other hand, some substances such as the inorganic salts increase the surface tension. A solution of 5 gm. mol. per litre of sodium chloride has a surface tension of 82 dyne cm.$^{-1}$.

In the case of a pure liquid there is no possibility of varying the composition of the surface layer. It follows that large films of pure liquid cannot be produced. For if a vertical film of pure water exists, the weight of the film requires that the surface tension at the upper part should be greater than at the lower part, since the surface tension at the upper part has the weight of the film to carry. As this is impossible, the film breaks. It is common experience that only small films and bubbles can be produced with pure water. But with some solutions, the case is different. If the solute lowers the surface tension, the stretching in the upper part of the vertical film causes a weakening of the concentration of the solute in the upper part of the film with a corresponding increase in the surface tension. This occurs to a marked degree with soap solutions, so that the surface tension is adjusted to compensate for the increased pull in the upper part of the film. Soap solutions are able to produce films and bubbles of great durability.

The surface layer differs in several ways from the bulk of the liquid. If the liquid is pure, the only change possible is a difference in density between the surface layer and the interior of the solution. But in the case of a solution there is a further possibility; the concentration of the solute may vary. Accepting the principle that

the potential energy of a system tends towards a minimum, and that the surface tension is a measure of the energy associated with the surface layer, it follows that the solute will move towards that condition which will make the surface tension a minimum. If the solute causes a lowering of the surface tension, it will be found to be more concentrated in the surface layer than in the interior of the liquid. On the other hand, if the solute causes an increase in surface tension, it will be less concentrated in the surface layer than in the interior. This can be established by thermodynamical reasoning, and is completely borne out by experiment. The proof is beyond the scope of this book, and the student is referred to more advanced works on the physics and chemistry of surface layers.*

This is in accord with the fact that highly soluble substances would be more concentrated in the interior of the solution than at the surface, owing to the great attraction between the water molecules and the molecules of the solute. The solute molecules are pulled into the interior, with increase in surface tension (p. 250). The opposite effect occurs in the case of slightly soluble substances.

The amount of substance transferred in this way from the interior of the liquid to the surface layer is called the **adsorption** per unit area of surface. Adsorption may therefore be either positive or negative. It is positive when the solute lowers the surface tension and enters the layer, and negative when it raises the surface tension and so leaves the surface layer. The latter case occurs with many inorganic salts.

The term adsorption is most commonly applied to the case of gases deposited or clinging to solid surfaces. Perhaps the most important case is that of charcoal, which can adsorb large quantities of many gases. It is used in producing high vacua. A vessel containing charcoal is in communication with the vacuum vessel. When a low pressure has been reached by pumping (p. 247), the vessel containing the charcoal is surrounded by liquid air. At this low temperature the charcoal adsorbs large quantities of the remaining gas, and so produces a great lowering of the pressure in the vacuum vessel. In some cases the gas adsorbed forms a solution in the solid, and diffuses into the interior. The name **sorption** has been given to the whole process.

The remarkable stability of soap films has received a great deal of investigation. It is now considered that the stability is due to a monomolecular layer at the surface (p. 286). The soap consists of long chain molecules having an extremely soluble group, such as

* E. K. Rideal, *An Introduction to Surface Chemistry*. N. K. Adam, *The Physics and Chemistry of Surfaces*.

COONa, at one end. This group forms a strong anchorage in the water, and the lateral attraction between the long molecules maintains a stable layer with sufficient mobility to increase the surface tension wherever the film is stretched. A freshly-formed soap film rapidly thins, and soon the characteristic interference colours are seen. These change as the film gets thinner, until eventually the film becomes so thin that it cannot produce interference, and it is then black. There is little doubt that the black film consists of two monomolecular layers of soap molecules with a small amount of water between them. The black film may also consist of two such double layers in contact. Any change from this to the thinner film is abrupt, and the thinner presents a sharp, though irregular boundary.

Thickness of surface film.—An estimate of the thickness of the surface film indicates that it is about molecular dimensions. The late Lord Rayleigh examined the thickness of an oil film on water by placing a very small amount of oil on the surface of clean water in a dish. By means of a movable barrier, the area of surface of the oil film could be varied as desired. On increasing the area and so diminishing the thickness of the oil layer, it was found that the surface tension remained constant until the thickness was reduced to about 5 $\mu\mu$ (micro-millimetres). At 1·6 $\mu\mu$ the surface tension increased rapidly, and at 1 $\mu\mu$ the surface tension was sensibly that of pure water. This layer is of the order of one molecule in thickness, and it may be concluded that when the layer of oil is so spread that the spacing of its molecules is such that they do not cover the water surface, the surface tension is that of pure water. Later experiments bear out this conclusion (p. 287).

Monomolecular layers.—The existence of surface layers one molecule in thickness has been proved definitely by Langmuir. Certain oils and fats are very slightly soluble. By taking a small quantity of a solution in benzene and dropping it on the surface of the water, the benzene evaporates and a layer of oil is obtained. From the area of the layer and the quantity of oil used, it was found that the layer was one molecule thick.

The experiment is carried out in a shallow trough of water. A light rod placed across the trough separates pure water at one end from the water whose surface is contaminated with the oil or fatty acid on the other. The rod is attached to a lever so that it can move horizontally along the surface. Weights added to the lever determine

the force on the rod required to keep it in equilibrium. This force is a measure of the difference of surface tension between the pure water and the oily water. A movable barrier enables the layer of oil to be pushed towards the counterpoised rod. By this means it was found that when the layer has such a great area that there are spaces between the oil molecules, that is, the layer does not cover the water, the surface tension does not differ appreciably from that of pure water. As the layer is diminished in area by pushing along the barrier, the surface tension slowly falls and the force trying to cause spreading increases. At this stage the molecules in the layer are mobile, as may be shown by placing dust particles on the surface. They can be blown about quite easily.

On further contraction of the layer, a stage is reached at which the force on the rod increases more rapidly and in a linear manner. The film has lost its mobility, as shown by dust particles being fixed. The behaviour of the film is analogous to that of a solid undergoing an elastic strain (p. 127). At the close of this stage a further squeezing causes the film to crumple visibly, and the spreading force remains nearly constant.

It was shown that such monomolecular layers act like two dimensional solids or liquids. In the mobile stage, the spreading force F, or difference between surface tensions of the clean and the contaminated surface, obeys a law similar to the gas law $pv=kT$, where k is the gas constant for one molecule. In this case, $Fa=kT$, where k is the same constant as before and a is the area of the monomolecular layer.

The explanation of these molecular layers given by Langmuir is that one end of the molecule has a considerable affinity for water, while the other has none. The molecules of the oils and fatty acids which produce monomolecular layers on water consist of chains, each link in the chain being CH_2, one end of the chain being CH_3 and the other $-OH$ or $-COOH$. The hydrocarbon group CH_3 has no affinity for water, while the $-OH$ or $-COOH$ has. This active end is held beneath the water surface, while the inactive CH_3 end projects above it. The mobile or expanded layer corresponds to the fluid state, and the melting point is the temperature at which the transition from the immobile to the mobile state takes place.

Adam classifies such films, or layers, formed by insoluble substances, under four heads.

(i) *Condensed films*, or those in which the molecules in the monomolecular layer are so closely packed that they are immobile and are steeply inclined to the surface.

(ii) *Gaseous films*, in which the molecules are so far separated that they have independent movement in the surface and exert a pressure

on the linear boundary, analogous to a gas pressure. Such an ideal case is never realised in practice, because the molecules, if large, will either dissolve or disappear by evaporation.

(iii) *Liquid expanded films*, in which the molecules adhere strongly to each other, but are not so closely packed together as in (i).

(iv) *Vapour expanded films* are those in which there is still adhesive force between the molecules, but not of sufficient magnitude to keep the molecules together in islands as in (i) and (iii). This class of film shades off into (ii).

Calming of sea waves by oil.—Several explanations have been given of the fact that oil poured upon the sea renders the waves less dangerous. All agree that the oil has no effect upon the height of large waves, but is active in suppressing the ripples produced by the wind. These ripples may, by the action of the wind, give rise to large waves. They may also give rise to dangerous breaking of the large waves. The late Lord Rayleigh explained the effect of the oil by saying that the wind, pushing the oil along the surface, increased the contamination, and so lowered the surface tension in advance of the ripple and left a cleaner surface with higher surface tension behind. The surface tension thus produces forces which oppose the motion of the surface produced by the wind, and so tends to prevent the formation of ripples.

The above explanation is not complete, because the surface tension is not lowered until the whole surface is covered by oil. It has, however, been shown that a film of oil which does not cover more than a small fraction of the surface is effective in damping ripples. It is more probable that the viscous resistance to displacement of the oil on the water plays the most important part in the damping of the ripples. Adam states that good spreading power on the surface of the water is important. Mineral oils are not effective, but in emergency they may be improved by melting stearine candles and mixing with the oil. The carboxyl group in the stearine molecules gives a good anchorage in the water.

Exercises on Chapter XII

1. Write an essay on *surface tension*. C.H.S.C.

2. What is meant by the *surface tension* of a liquid?
Describe and explain a method of measuring the surface tension of water. C.H.S.C.

3. What do you understand by "surface tension"?
Describe some natural phenomena depending upon surface tension. Explain fully a method of measuring the surface tension of water. Lond. H.S.C.

4. Give a brief outline of a method of measuring the surface tension of a liquid.

A glass plate, of length 10·0 cm., breadth 1·54 cm., and thickness 0·20 cm., weighs 8·2 gm. in air. If it is held vertically, with its long side horizontal, and its lower half immersed in water, what will be its apparent weight? (Surface tension of water = 73 dynes per cm.) C.H.S.C.

5. Describe experiments to illustrate the phenomenon of surface tension.

A glass tube of 1 mm. internal diameter is held vertically with one end below the surface of some water, and the water level inside the tube rises 2·4 cm. above that outside. Deduce from first principles a value for the surface tension of water. What is the probable cause of the erroneous value obtained? C.H.S.C.

6. Describe the capillary tube method of measuring the surface tension of a liquid. Why is it unsuitable for measurements of surface tension at temperatures other than that of the surroundings? Design a piece of apparatus with which this difficulty might be overcome by measuring the pressure necessary to force the meniscus back to the level of the surrounding liquid. O. & C.H.S.C.

7. Describe a method of measuring the surface tension of water by means of a capillary tube.

The stem of a common hydrometer is a circular cylinder of diameter 2 mm. It floats, with its stem wetted, in alcohol, whose specific gravity is 0·796, and surface tension 25·5 dynes per cm. Calculate how much deeper it floats than if the alcohol had had zero surface tension. C.H.S.C.

8. How is the difference in the curvatures of a water meniscus and a mercury meniscus explained?

Water rises to a height of 5·0 cm. in a certain capillary tube. In the same tube the level of a mercury surface is depressed by 1·54 cm. Compare the surface tensions of water and mercury. (The specific gravity of mercury is 13·6, the angle of contact for water is 0° and for mercury 130°.) Lond. Int. Sci.

9. Describe the capillary tube method of measuring the surface tension of a liquid, proving the expression for the rise of liquid in the tube.

A capillary tube of internal diameter 1 mm. and external diameter 5 mm. hangs vertically from the arm of a balance, the lower end of the tube being in a liquid of surface tension 40 dyne cm. Assuming that the liquid wets the tube, what is the change in the apparent weight of the tube due to surface tension? ($g = 980$ cm. sec.$^{-2}$.) L.H.S.C.

10. Explain *surface tension, angle of contact.* Show how the existence of an acute angle of contact and of a pressure difference due to curvature accounts for the rise of a liquid in a capillary tube.

A tube of 1 mm. bore is dipped into a vessel containing a liquid of density 0·8 gm. cm.$^{-3}$, surface tension 30 dyne cm.$^{-1}$ and contact angle zero. Calculate the length which the liquid will occupy in the tube when the tube is (*a*) held vertical, (*b*) inclined to the vertical at an angle of 30°. Lond. Int. Arts.

11. Obtain an expression for the rise (or fall) of a liquid in a vertical capillary tube dipped into a wide vessel containing the liquid. What determines whether the liquid rises or falls ?

A U-tube is made up of two capillaries of bore 1 mm. and 2 mm. respectively. The tube is held vertically and partially filled with a liquid of surface tension 49 dyne $cm.^{-1}$ and zero contact angle. Calculate the density of the liquid if the difference in the levels of the menisci is 1·25 cm.
Lond. Int. Sci.

12. A capillary tube of 0·5 mm. bore stands vertically in a wide vessel containing a liquid of surface tension 30 dyne $cm.^{-1}$, density 0·8 gm. $cm.^{-3}$ and zero contact angle. Calculate the height (h) to which the liquid will rise in the tube. Establish any formula which you employ.

What will happen if the length of the capillary projecting from the surface of the liquid is less than h ? Lond. Int. Sci.

13. Describe a method for the determination of the surface tension of a soap solution, and prove any formula required for the reduction of the observations.

Find the difference of the levels of the mercury in the two limbs of a U-tube if the diameter of the bore of one limb is 1 mm. and of the other 8 mm. The surface tension of mercury is 440 C.G.S. units, its density 13·6 gm. per c.c., and the angle of contact with the walls of the tube 140°.
J.M.B.H.S.C.

14. Find an expression for the difference of pressure between the inside and outside of a soap-bubble.

Two bubbles, of the same radius, are blown on one end of each of two open tubes. Describe and explain what happens when the tubes are connected together at their free ends. O. & C.H.S.C.

15. Describe in detail how you would determine the surface tension of water by capillary elevation. Why does the water in a glass capillary tube rise above the level of that outside, while in a tube of paraffin wax it sinks below ? Is it necessary to take into account the material of the tube in working out the surface tension of the liquid ?

What would be the pressure inside a small air-bubble of 0·1 mm. radius, situated just below the surface of water ? (Take the surface tension of water as 70 dynes per cm. and atmospheric pressure as $1{\cdot}013 \times 10^6$ dynes/sq. cm.) O.H.S.C.

16. Define *surface tension* (T), and show that the pressure inside a spherical soap-bubble of radius r exceeds that outside by $4T/r$. If this pressure is balanced by that due to a column of oil (sp. gr. 0·80) 1·4 mm. high when $r=1$ cm., find the surface tension of the solution. State the unit in which your result is expressed. Lond. Int. Sci.

CHAPTER XIII

WAVES

Wave motion.—A disturbance of any kind which travels may be called a wave. The term, however, is generally reserved for a disturbance which travels without change of form.

As a simple example, think of a rope, one end of which is held in the hand. On giving the hand a sharp jerk to one side, a pulse is seen to travel along the rope, provided that the rope is not stretched tight. If the rope is tight there will still be a pulse produced on giving the jerk, but this pulse may travel so quickly that the eye cannot follow it. In any case, if the rope is sufficiently long, the pulse is very nearly a true wave. It travels along the rope, and keeps its shape while travelling.

Other types of wave are very well known: for example, ripples spread outwards along the surface of a pond when a stone is thrown into it. These ripples become feebler through attenuation as the circles become bigger. The larger waves seen on the sea are not of the same character as the ripples, but may be looked upon as true waves when they travel with constant shape.

Then again the waves in the air which produce the sensation of sound are of a still different type, and are invisible. They will be studied later (p. 300). Electromagnetic waves, ranging from those used in wireless transmission, through light waves, to the shortest known waves, such as gamma rays and cosmic rays, are further examples. They will not be studied here, as our attention is confined to waves of a mechanical type, but many of the wave equations apply to waves in general, whatever the particular type may be.

General equation of wave motion.—The disturbance which travels may have a variety of forms. In the rope or the ripple it is a displacement which takes place at right angles to the direction in which the wave is travelling. Let Ox (Fig. 205) represent the rope or the surface of the water, and take the axis Oy in the direction of the displacement. If a displacement be given at O, at a certain time,

the pulse may have travelled to the position ABC at a later time. The curve ABC may have a variety of shapes, but some equation can be found to represent it. The commonest type is represented by a sine or cosine curve, but for the moment we will write it $y=f(x)$, where the function f is quite general.

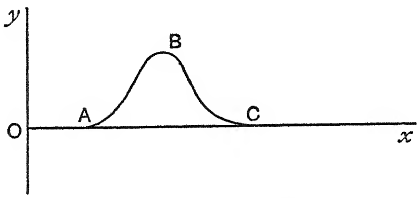


FIG. 205.—WAVE FORM.

Since the pulse ABC travels along Ox it must have a velocity (v), and after t seconds it will have travelled a distance vt. The complete equation for the wave motion must then be $y=f(x-vt)$, because this represents a displacement which travels along Ox with velocity v and with shape unchanged. After a lapse of t sec. the wave has travelled a distance vt. Moving the origin to the right by this distance and calling x' the new abscissa, $x=x'+vt$, and on substituting for x, $y=f(x'+vt-vt)$ or $y=f(x')$. That is, the curve has the same equation referred to the new origin as it had t sec. earlier with respect to the old origin. Hence the wave $y=f(x-vt)$ travels with velocity v and shape unchanged.

In a similar manner the equation $y=f(x+vt)$ represents a wave travelling in the direction xO, because the origin must now be moved in the negative direction, that is, to the left, in order to preserve the equation. For $x=x'-vt$ or $y=f(x'-vt+vt)=f(x')$.

Simple harmonic wave.—In Nature the waves which occur most frequently are produced by vibrating bodies, that is, bodies which possess simple harmonic motion, or motion represented by the equation $y=a\sin\omega t$ (p. 90). If the hand which holds the end of the rope (p. 291) executes this motion, the end of the rope will do likewise, and the equation of its motion is $y=a\sin\omega t$. As in Chapter IV, a is the amplitude and $\omega=2\pi n$, where n is the frequency of the vibration ;

$$\therefore\ y=a\sin 2\pi nt$$
$$=a\sin 2\pi\frac{t}{T},$$

where T is the periodic time of vibration, that is, $\frac{1}{n}$.

The distance travelled by the wave while the end makes one complete vibration is called the wave-length, λ (Fig. 206), and therefore in one second the wave travels a distance $n\lambda$,

or $\quad v = n\lambda = \frac{\lambda}{T}$.

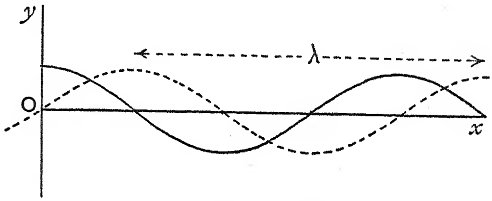


FIG. 206.—SINE WAVE.

Now the equation of the wave must be of the form $y = f(x - vt)$, and this is consistent with the equation

$$y = a \sin 2\pi \left(\frac{x}{\lambda} - \frac{t}{T}\right)$$

$$= a \sin \frac{2\pi}{\lambda}\left(x - \frac{\lambda}{T} t\right)$$

$$= a \sin \frac{2\pi}{\lambda}(x - vt).$$

It is also consistent with the motion of the end at the origin O, for when $x = 0$,

$$y = -a \sin 2\pi \frac{t}{T}.$$

The negative sign arises because, when $t = 0$, $y = a \sin \frac{2\pi}{\lambda} x$. This is the equation of the curve shown in dotted line in Fig. 206, and as this curve moves forwards, the end of the rope at O moves downwards, so that the equation of its motion is $y = -a \sin 2\pi \frac{t}{T}$.

Again, if t in the equation $y = a \sin 2\pi \left(\frac{x}{\lambda} - \frac{t}{T}\right)$ be increased by the amount T,

$$y = a \sin 2\pi \left(\frac{x}{\lambda} - \frac{t+T}{T}\right)$$

$$= a \sin \left\{2\pi\left(\frac{x}{\lambda} - \frac{t}{T}\right) - 2\pi\right\}.$$

The angle is decreased by 2π, and its sine therefore has the same value as at the beginning of the interval T. Similarly if x is increased by the amount λ,

$$y = a \sin \left\{2\pi\left(\frac{x}{\lambda} - \frac{t}{T}\right) + 2\pi\right\},$$

and at any instant y has the same value at points separated by distance λ.

Transverse and longitudinal waves.—The rope has been chosen as an illustration, but it must be understood that the above equation applies to all waves in which the particles of the medium execute simple harmonic motion. As any other periodic motion may be resolved into a series of sines and cosines, all waves may be represented by such a series, but only simple sine waves will be considered here. There is one characteristic common to waves in a rope, or stretched string and to ripples, which is that the motion of the particles is at right angles to the direction in which the waves travel. Such are called **transverse waves.**

In sound waves the motion of the particles is in the same direction as that in which the waves are travelling. These are called **longitudinal waves.** These longitudinal motions of the particles cause compressions and rarefactions, as will be seen later (p. 298). Solids, owing to the possession of compressibility, as well as rigidity and tensile elasticity, can transmit both longitudinal and transverse waves, but gases, having compressibility only, can only transmit longitudinal waves. Liquids can transmit longitudinal waves, and at their surface, on account of surface tension, can transmit ripples, which are transverse waves.

Particle velocity and acceleration.—Each particle of the medium transmitting a wave moves in a line, its amplitude of vibration being a. Its velocity must not be confused with the velocity, v, of the wave. If the displacement at a point in the medium is y, the velocity of the particle at any instant is the quantity $\frac{dy}{dt}$, and may be obtained from the wave equation $y=a\sin 2\pi\left(\frac{x}{\lambda}-\frac{t}{T}\right)$.

$$\begin{aligned}\frac{dy}{dt}&=-\frac{2\pi a}{T}\cos 2\pi\left(\frac{x}{\lambda}-\frac{t}{T}\right)\\&=\frac{2\pi a}{T}\sin\left\{2\pi\left(\frac{x}{\lambda}-\frac{t}{T}\right)-\frac{\pi}{2}\right\}\\&=\frac{2\pi a}{T}\sin 2\pi\left(\frac{x-\frac{\lambda}{4}}{\lambda}-\frac{t}{T}\right).\end{aligned}$$

This may also be represented by a sine curve. Its amplitude is $\frac{2\pi a}{T}$, and it is situated a quarter of a wave-length from the displacement curve. If the full-line curve in Fig. 207 is the curve of displacement,

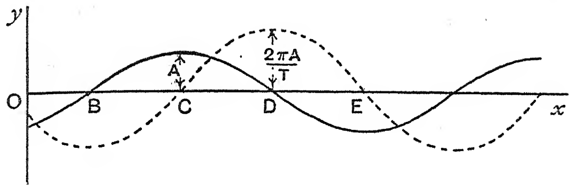


FIG. 207.—PARTICLE VELOCITY AND ACCELERATION.

the velocity curve is the dotted line. At B and D the particle has greatest velocity $\left(\frac{2\pi a}{T}\right)$, and it is negative at B and positive at D. At C and E the particle velocity is zero.

In a similar way the acceleration of a particle is

$$\frac{d^2y}{dt^2} = -\frac{4\pi^2 a}{T^2}\cos 2\pi\left(\frac{x-\frac{\lambda}{4}}{\lambda}-\frac{t}{T}\right)$$

$$= \frac{4\pi^2 a}{T^2}\sin\left\{2\pi\left(\frac{x-\frac{\lambda}{4}}{\lambda}-\frac{t}{T}\right)-\frac{\pi}{2}\right\}$$

$$= \frac{4\pi^2 a}{T^2}\sin 2\pi\left(\frac{x-\frac{\lambda}{2}}{\lambda}-\frac{t}{T}\right).$$

That is, the particle acceleration varies harmonically between $+\frac{4\pi^2 a}{T^2}$ and $-\frac{4\pi^2 a}{T^2}$, and may be represented by a sine curve half a wave-length from the displacement curve.

Also, the wave velocity is $\frac{dx}{dt}$;

$$\therefore \frac{\text{particle velocity}}{\text{wave velocity}} = \frac{\frac{dy}{dt}}{\frac{dx}{dt}} = \frac{dy}{dx},$$

and is thus the slope, at any point, of the displacement curve.

Velocity of transverse wave in stretched string.—If the string is so thin that any bending moment (p. 145) may be neglected, and any part of the string is displaced laterally from its equilibrium position, the only restoring force is due to the tension in the string. If f is the total stretching force in the string, that is (tension × cross-section), and AB (Fig. 208) is a very short length dx of the string displaced from the line EF, the restoring force is represented by GH, and is the resultant of the two forces GC and GD, each equal to f.

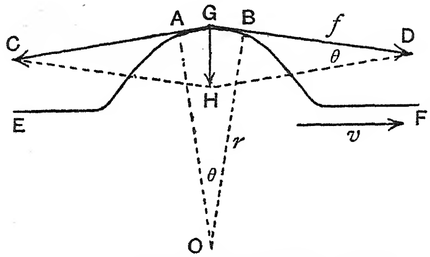


FIG. 208.—VELOCITY OF WAVE IN STRING.

The displacements are greatly exaggerated in the figure. From the diagram it is seen that if AB is very small, GHD and ABO are similar triangles, where O is the centre of curvature of the element of string AB;

$$\therefore \ \frac{\mathrm{GH}}{\mathrm{GD}}=\frac{dx}{\mathrm{AO}}=\frac{dx}{r};$$

$$\therefore \ \mathrm{GH}=\frac{\mathrm{GD}\,.\,dx}{r}=\frac{f\,dx}{r}.$$

If the string has mass m per unit length, the mass of AB is $m\,dx$, and its acceleration is

$$\frac{\text{force}}{\text{mass}}=\frac{f\,dx}{rm\,dx}=\frac{f}{rm}.$$

Now, to express the acceleration in terms of the velocity v of the wave travelling from E to F, remember that the string at the point B has particle velocity $v\,.\left(\frac{dy}{dx}\right)_B$ (p. 293), and the particle velocity of the string at A is $v\left(\frac{dy}{dx}\right)_A$. As the wave travels over the distance AB, the velocity of an element of string B changes from $v\left(\frac{dy}{dx}\right)_B$ to $v\left(\frac{dy}{dx}\right)_A$, since the condition of the string shown at A has now reached B. The acceleration of a point on the string is therefore

$$\frac{v\left(\frac{dy}{dx}\right)_B-v\left(\frac{dy}{dx}\right)_A}{dt},$$

where dt is the time taken for the wave to travel the distance AB or dx. $\left(\frac{dy}{dx}\right)_B$ is the slope of the displacement curve at B and $\left(\frac{dy}{dx}\right)_A$ that at A, so that when both of these are small,

$$\left(\frac{dy}{dx}\right)_B - \left(\frac{dy}{dx}\right)_A = \theta = \frac{dx}{r}.$$

The particle acceleration is thus $\frac{v\,dx}{r\,dt} = \frac{v^2}{r}$, since $\frac{dx}{dt} = v$. But it has been shown above that the acceleration is $\frac{f}{rm}$;

$$\therefore \quad \frac{v^2}{r} = \frac{f}{rm},$$

$$v = \sqrt{\frac{f}{m}} = \sqrt{\frac{\text{stretching force}}{\text{mass per unit length}}}.$$

This expression is not valid if the displacements are very large, but holds in the ordinary case of the stretched string used in musical instruments.

Longitudinal wave.—The representation on a diagram of a longitudinal wave is not so easy as that of a transverse wave, because the displacement is in the direction of the wave. In the transverse wave the diagram may be an actual picture of the string. If particles of the medium transmitting a longitudinal wave are at A, B, C, D and E (Fig. 209) when normally at rest at these points, then

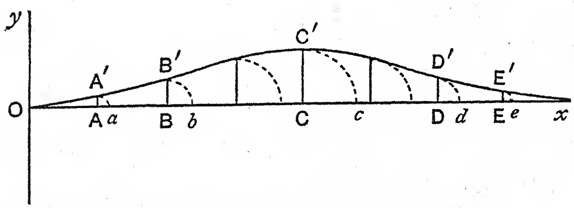


FIG. 209.—REPRESENTATION OF LONGITUDINAL WAVE.

when the wave passes they may, at some particular moment, be at a, b, c, d and e. On describing arcs of circles aA′, bB′ and cC′, etc., the points A′, B′ and C′, etc., are obtained, and the curve A′B′C′D′E′ represents to scale the state of the medium at that moment. Whether the medium is air, or a solid rod, the points A, B and C represent layers at right angles to the direction of propagation of the wave. Each layer is moved forwards or backwards by the amount Aa, Bb,

Cc, etc. Displacements forwards are plotted upwards and those backwards are plotted downwards, as in Fig. 210. If AB′CD′E is a sine curve, the medium is evidently compressed in the neighbour-

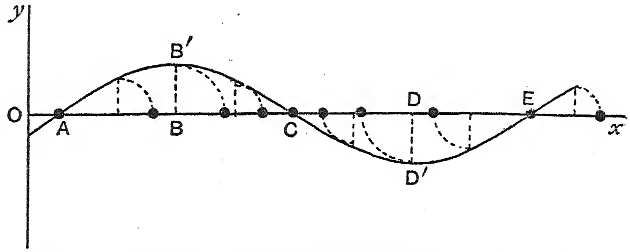


FIG. 210.—LONGITUDINAL WAVE REPRESENTED BY A SINE CURVE.

hood of points represented by C and rarefied at points such as A and E. As the wave travels forwards, these compressions and rarefactions move onwards.

Referring again to Fig. 209; if the displacement Aa, Bb, etc., is represented by y, Bb – Aa is δy, the change in displacement over the distance AB or δx. The quantity $-\dfrac{\delta y}{\delta x}$, or in the limit when AB is very small, $-\dfrac{dy}{dx}$, is the compression of the layer AB. The negative sign is taken, because y must decrease with increasing x for the medium to be compressed, as it is in Fig. 210, from B to D. Thus when the curve AB′CD′E has a negative slope $\dfrac{dy}{dx}$ is negative, and the medium is in compression. Where the slope, that is, $\dfrac{dy}{dx}$, is positive, the medium is rarefied.

Velocity of compression wave.—Imagine two parallel planes drawn in the medium at right angles to Ox (Fig. 211), one through A and

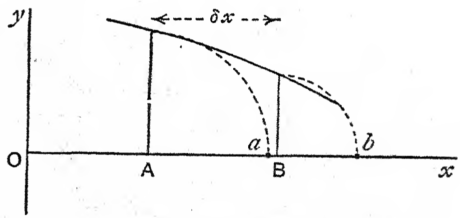


FIG. 211.—VELOCITY OF COMPRESSION WAVE.

the other through B. Draw an area s round A and B in these planes, forming a prism of volume $s\,dx$ in the medium, with sides parallel to

Ox. If ρ is the density, $\rho s\, dx$ is the mass of medium in this prism. The compression at A is $\left(\dfrac{dy}{dx}\right)_A$, and if k is the bulk elasticity of the medium the pressure at A due to the compression is $k\left(\dfrac{dy}{dx}\right)_A$ (p. 128). This gives a force $sk\left(\dfrac{dy}{dx}\right)_A$ on the base of the prism at A. There is a similar force of $sk\left(\dfrac{dy}{dx}\right)_B$ over the base at B, so that there is a resultant force $sk\left\{\left(\dfrac{dy}{dx}\right)_A - \left(\dfrac{dy}{dx}\right)_B\right\}$ on the prism due to the difference in compression at A and B. The acceleration of the medium in the prism is therefore

$$\frac{\text{force}}{\text{mass}} = \frac{sk\left\{\left(\frac{dy}{dx}\right)_A - \left(\frac{dy}{dx}\right)_B\right\}}{\rho s\,\delta x} = \frac{k\left\{\left(\frac{dy}{dx}\right)_A - \left(\frac{dy}{dx}\right)_B\right\}}{\rho\,\delta x}.$$

The particle velocity at A is $v\left(\dfrac{dy}{dx}\right)_A$ (p. 295) and at B is $v\left(\dfrac{dy}{dx}\right)_B$, so that the ratio of the change in velocity of a layer as the wave passes over the distance dx to the time taken, δt, is

$$\frac{v\left\{\left(\frac{dy}{dx}\right)_A - \left(\frac{dy}{dx}\right)_B\right\}}{\delta t},$$

and this also is the acceleration;

$$\therefore \quad \frac{v\left\{\left(\frac{dy}{dx}\right)_A - \left(\frac{dy}{dx}\right)_B\right\}}{\delta t} = \frac{k\left\{\left(\frac{dy}{dx}\right)_A - \left(\frac{dy}{dx}\right)_B\right\}}{\rho\,\delta x},$$

$$v\frac{\delta x}{\delta t} = \frac{k}{\rho}.$$

Now $\dfrac{\delta x}{\delta t}$ is the velocity of the wave v;

$$\therefore \quad v^2 = \frac{k}{\rho}.$$

$$v = \sqrt{\frac{k}{\rho}},$$

If the wave is travelling in a solid rod, the elasticity is Young's modulus (e) (p. 127), and

$$\text{velocity} = \sqrt{\frac{e}{\rho}}.$$

If the wave is in air, the elasticity may have one of two forms, according to whether the changes occurring are considered to take place so slowly that heat diffusion causes the temperature to remain constant, or whether they occur so rapidly that there is no leak of heat from one layer to another. In the former case, the elasticity is calculated from the isothermal relation

$$pv = \text{const.},$$

that is, from Boyle's law (p. 174),

$$p = \frac{c}{v},$$

$$\frac{dp}{dv} = -\frac{c}{v^2}.$$

Now,
$$\text{elasticity} = \frac{\text{stress}}{\text{strain}} \quad \text{(p. 128)}$$

$$= \frac{dp}{\frac{dv}{v}} = v\frac{dp}{dv} = -\frac{c}{v} = p.$$

The negative sign occurs because $\frac{dp}{dv}$ is essentially negative, increasing pressure causing decreasing volume. The elasticity is therefore equal to the pressure, and

$$\text{velocity of wave} = \sqrt{\frac{p}{\rho}}.$$

This result is due to Newton. On putting in the values

$$p = 76 \times 13{\cdot}6 \times 981 \text{ dynes per cm.}^2$$

and
$$\rho = 0{\cdot}001293 \text{ gm. per c.c.}$$

for air at normal temperature and pressure,

$$v = \sqrt{\frac{76 \times 13{\cdot}6 \times 981}{0{\cdot}001293}}$$

$$= 28000 \text{ cm. sec.}^{-1}.$$

This is less than the observed value. It was pointed out by Laplace that the adiabatic elasticity should have been taken, as

the latter of the two above alternatives is the more likely to be correct. In this case

$$pv^{\gamma}=\text{const.} \quad \text{(p. 211)}; \quad \text{and for air } \gamma=1\cdot41;$$

$$\therefore \ p=cv^{-\gamma}$$

$$-\frac{dp}{dv}=\gamma cv^{\gamma-1};$$

$$\text{elasticity}=-v\frac{dp}{dv}=\gamma cv^{\gamma}=\gamma p;$$

$$\therefore \ \text{velocity of wave}=\sqrt{\frac{\gamma p}{\rho}}$$

$$=\sqrt{\frac{1\cdot41\times76\times13\cdot6\times981}{0\cdot001293}}$$

$$=33250 \text{ cm. sec.}^{-1}.$$

This is very close to the observed value of the velocity of sound in air at normal temperature and pressure, and justifies the use of the adiabatic elasticity.

Interference of waves.—Provided that the displacements are not excessive, two or more waves may travel independently through a medium at the same time. The resultant displacement at any place is then the sum of the displacements produced by the separate waves at any particular instant. In the case of two waves, the resultant displacement is the arithmetic sum of the separate displacements where these are of the same sign, and the difference where the two have opposite signs. Thus the displacement due to the first wave may be increased at some points by the presence of the second wave and diminished at other points. The waves are said to **interfere**, and the phenomenon is called **interference.** The name is in some ways unfortunate, since what is really meant is that each wave preserves its independent existence and does *not* interfere with the other. The resultant is the algebraic sum of the effects of the two waves at each place.

The name " interference " is, however, so long established and so well recognised that its use is not likely to be discontinued.

Interference is illustrated in Fig. 212, where the ripples on the surface of mercury are shown. They are produced by two pointed wires, attached together to the prong of a tuning fork. They have thus the same frequency, and produce two sets of ripples which

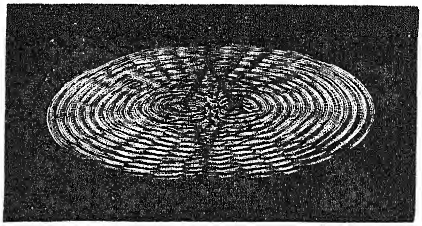


FIG 212.—INTERFERENCE OF MERCURY RIPPLES.

travel in circles from them. The surface is viewed for an instant, and the points of maximum disturbance are seen as lightly-shaded circles. These are crossed by darker rays passing through points where the two sets of waves together produce minimum disturbance.

Stationary vibration.—A very important example of interference is seen when two waves of equal frequency and amplitude travel through a medium in opposite directions. The equations for the waves are

$$y = a \sin 2\pi\left(\frac{x}{\lambda} - \frac{t}{T}\right) \quad \text{and} \quad y = a \sin 2\pi\left(\frac{x}{\lambda} + \frac{t}{T}\right) \quad \text{(p. 292).}$$

The resultant displacement is then

$$\begin{aligned} y &= a \sin 2\pi\left(\frac{x}{\lambda} - \frac{t}{T}\right) + a \sin 2\pi\left(\frac{x}{\lambda} + \frac{t}{T}\right) \\ &= 2a \sin 2\pi \frac{x}{\lambda} \cos 2\pi \frac{t}{T}. \end{aligned}$$

The x's and the t's are thus separated, and at any given place in the medium the particle executes a vibration $\cos 2\pi \frac{t}{T}$ with amplitude $2a \sin 2\pi \frac{x}{\lambda}$. At points for which $x = 0, \frac{\lambda}{2}, \lambda, \frac{3\lambda}{2}$, etc., $\sin 2\pi \frac{x}{\lambda} = 0$ and the amplitude of vibration is zero. Such points are shown at O, A, B and C in Fig. 213. They are called **nodes**, for the medium is always at rest at these points. On the other hand, if $x = \frac{\lambda}{4}, \frac{3\lambda}{4}, \frac{5\lambda}{4}$, etc., the amplitude has the values $2a$, and the displacements are alternately

positive and negative. Such points are D, E and F (Fig. 213), and are called **antinodes.**

This state of affairs is represented by a thin line curve for the wave

$$y = a \sin 2\pi \left(\frac{x}{\lambda} - \frac{t}{T}\right),$$

and a dotted line curve for

$$y = a \sin 2\pi \left(\frac{x}{\lambda} + \frac{t}{T}\right).$$

The thick line gives the curve of resultant displacement. In Fig. 213 (*a*) the constituent waves are in the same condition. In (*b*) each

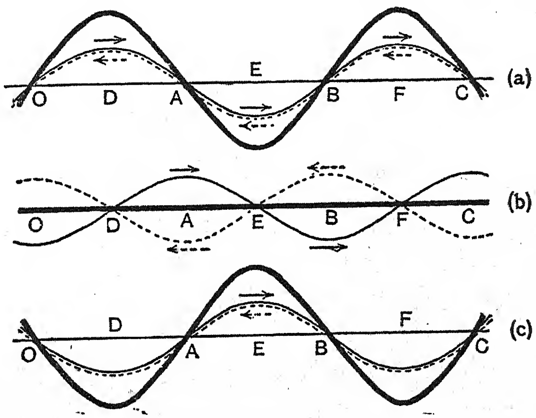


FIG. 213.—WAVES PRODUCING STEADY VIBRATION.

wave has moved forward a distance $\frac{\lambda}{4}$ in its own direction, and the resultant displacement is for this instant everywhere zero. Another advance of $\frac{\lambda}{4}$ and the condition (*c*) is reached. Two further advances of $\frac{\lambda}{4}$ would produce the condition (*a*) again.

Such a motion is a **steady vibration.** It is sometimes called stationary wave motion, but it differs in an important point from a wave motion, because each part of the medium moves backwards and forwards without the advancing of a pulse in any direction. A wave motion is essentially a phenomenon in which some state of disturbance travels from one place to another.

It will be noticed that the distance between consecutive nodes is $\frac{\lambda}{2}$ or half the wave-length of either constituent wave. The wave-length is thus the distance between alternate nodes or alternate antinodes.

The above applies to all simple harmonic waves, whether the transverse motion of a stretched string or the longitudinal waves in a column of air. The conditions of production, however, differ in various cases.

Vibration of stretched strings.—On plucking or striking a stretched string, a transverse wave is started, which on reaching a fixed end is reflected. The reflected wave together with the direct wave set up a state of steady vibration. As both ends of the string are fixed, reflection occurs at both ends, and a steady state of vibration of the string can only be reached if the waves reflected from one end coincide in phase with those travelling towards the other end. With a steady state of vibration the ends of the string must be nodes, because they are fixed. The simplest form of vibration is then, as in Fig. 214 (*a*), with an antinode in the middle of the string. The length l of the string is then $\frac{\lambda}{2}$ (above), where $n\lambda = v = \sqrt{\frac{f}{m}}$ (p. 297);

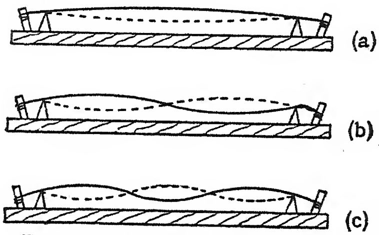


FIG. 214.—MODES OF VIBRATION OF A STRETCHED STRING.

$$\therefore \; n = \frac{1}{\lambda}\sqrt{\frac{f}{m}} = \frac{1}{2l}\sqrt{\frac{f}{m}}.$$

This is known as the **fundamental** form of vibration of the string. The next possible mode of vibration is shown in (*b*). There is a node in the middle and $\lambda = l$; $\therefore \; n = \frac{1}{l}\sqrt{\frac{f}{m}}$. Similarly in (*c*) there are two nodes besides those at the ends, and $\lambda = \frac{2}{3}l$, or $n = \frac{3}{2l}\sqrt{\frac{f}{m}}$. Thus the various possible forms of vibration have frequencies proportional to 1 : 2 : 3 : ... , etc.

An account of the notes emitted by the string vibrating will be found in books on Sound.

Vibration of air column.—A train of reasoning similar to the above shows that a column of air confined in a cylindrical tube may be

set in steady vibration. But there are here two possibilities. At a closed end of the tube reflection occurs with a node of displacement, while an end open to the atmosphere is at or near a node of pressure, that is, an antinode of displacement. Thus with a tube open at both ends, the ends are antinodes and there is a node in the middle of the tube. The simplest form of vibration therefore has wave-length $\lambda = 2l$, and $n\lambda = v = \sqrt{\frac{k}{\rho}}$ (p. 299), where l is the length of the tube;

$$\therefore \quad n = \frac{1}{2l}\sqrt{\frac{k}{\rho}}.$$

The next mode of vibration has, like the string, a frequency

$$n = \frac{1}{l}\sqrt{\frac{k}{\rho}},$$

and so on.

If one end of the tube is open and the other closed, one end is an antinode and the other a node,

$$\therefore \quad \lambda = 4l \quad \text{and} \quad n = \frac{1}{4l}\sqrt{\frac{k}{\rho}}.$$

For the next form of vibration there must be an antinode and a node in the tube, because antinodes and nodes must alternate;

$$\therefore \quad l = \frac{3\lambda}{4} \quad \text{and} \quad n = \frac{3}{4l}\sqrt{\frac{k}{\rho}}.$$

For the next,

$$n = \frac{5}{4l}\sqrt{\frac{k}{\rho}},$$

and so on. For a study of the notes produced the student is referred to books on Sound.

Vibrating rod.—If a wooden rod be clamped at its middle point and stroked with a resined cloth, it may be set in longitudinal vibration; or a glass rod rubbed with a wet cloth may be used. Since the rod is free at both ends, these are antinodes, and the fundamental has frequency

$$n = \frac{1}{2l}\sqrt{\frac{e}{\rho}},$$

where e is Young's modulus.

Owing to the great value of e this fundamental frequency is very high, and the question of the higher frequencies is not of practical importance.

Waves on water.—Everyone is familiar with the waves which occur on the sea, or when a stone or heavy body is plunged into a pond. Such waves are transverse, the surface moving up and down, while the wave travels horizontally. But the water being incompressible, a transverse motion at or near the surface must be accompanied by some longitudinal motion. If this were not the case there would be a cavity under each crest and an enormous compression under a hollow. As this is not so, there must be a movement of liquid from hollow to crest to preserve the continuity of the liquid. It is possible from the equation expressing this continuity to find the velocity of such waves, but a less general and more descriptive

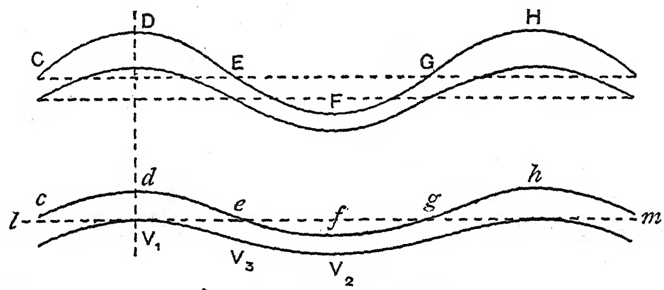


FIG. 215.—WAVES ON WATER.

method will be adopted here. If CDEFGH (Fig. 215) is a section of the actual surface of the water at a given instant, then *cdefgh* is a section of a surface in the water drawn at a depth in the water at the same instant. Each particle in a vertical line, say D*d*, executes vertical simple harmonic motion in the same phase and periodic time T, but the amplitude decreases as the depth increases. That this is so follows from the fact that at the bottom, the amplitude must be zero, but in deep water the amplitude has become zero long before the bottom is reached (see p. 312).

In order to produce such a motion, without discontinuity, the water must pass from hollows to crests. Since the crests and hollows pass any point periodically, each particle of the water has a horizontal oscillation which must have the same periodic time as the vertical oscillation. If this were not so there would not be a permanent wave transmission, the wave would continually be changing

in type. If the velocity of the wave, say from left to right (Fig. 215), is v, let us imagine an equal and opposite velocity to be superimposed on the medium. This would maintain the wave at rest while the medium streamed past it with velocity v. The lines CDEFGH and *cdefgh* now become stream-lines. The crests and hollows are supposed to be in parallel lines, and if a slice of unit thickness, of which the diagram is a section, be taken, the parts CDEFGH and *cdefgh* indicate stream-tubes. From p. 205 the velocity of the medium is greatest at the narrowest parts of the stream-tubes such as f, and least at the widest parts such as d.

If V_1 is the resultant velocity of the water at d,

$$V_1 = v - \left(\frac{dx}{dt}\right)_1,$$

where x is the horizontal particle displacement due to the horizontal oscillation. Also the velocity V_2 at f is

$$V_2 = v + \left(\frac{dx}{dt}\right)_2,$$

$\left(\frac{dx}{dt}\right)_1$ and $\left(\frac{dx}{dt}\right)_2$, being the velocities due to oscillation at d and f.

Since V_1 is the minimum resultant horizontal velocity and v is constant, $\left(\frac{dx}{dt}\right)_1$ is the maximum oscillatory velocity from left to right. Similarly $\left(\frac{dx}{dt}\right)_2$ is the maximum oscillatory velocity from right to left, and there is a zero value at e, half-way between d and f.

If the vertical oscillation of any particle is given by

$$y = a \sin 2\pi \frac{t}{T},$$

and the horizontal oscillatory displacement by

$$x = b \sin\left(2\pi \frac{t}{T} + \theta\right),$$

$$\frac{dx}{dt} = \frac{2\pi}{T}\, b \cos\left(2\pi \frac{t}{T} + \theta\right)$$

$$= \frac{2\pi}{T}\, b \sin\left(2\pi \frac{t}{T} + \theta + \frac{\pi}{2}\right).$$

Now this has its maximum value at d, where y is greatest and at f where y is negative, but of maximum negative value ;

$$\therefore\ \theta+\frac{\pi}{2}=0, \quad \text{or} \quad \theta=-\frac{\pi}{2};$$

$$\therefore\ \frac{dx}{dt}=\frac{2\pi}{T}\,b\sin 2\pi\frac{t}{T}$$

and $$x=b\sin\left(2\pi\frac{t}{T}-\frac{\pi}{2}\right).$$

Thus the vertical and the horizontal oscillations have the same periodic time T and differ in phase by $\frac{\pi}{2}$. Their resultant is therefore an elliptical motion of semi-major and minor axes a and b (p. 104).

In order to find the relation between a and b, Bernouilli's theorem (p. 207) may be applied to the stream-line $cdefgh$:

$$gh+\frac{p}{\rho}+\tfrac{1}{2}V^2=\text{const.}$$

Taking lm, the undisturbed horizontal plane, as datum level,

at d, $$h=a, \quad p=p_1,$$

and $$V_1=v-\frac{2\pi}{T}\,.\,b=v-\frac{2\pi}{\lambda}\,vb=v\left(1-\frac{2\pi}{\lambda}\,b\right),$$

since the particle makes a complete oscillation in time T, while the wave travels through a wave-length λ; or, $v=\lambda/T$.

Similarly, at f, $\quad h=-a,\ p=p_2$ and $V_2=v\left(1+\frac{2\pi}{\lambda}\,b\right)$.

Bernoulli's equation then gives

$$ga+\frac{p_1}{\rho}+\tfrac{1}{2}V_1{}^2=-ga+\frac{p_2}{\rho}+\tfrac{1}{2}V_2{}^2,$$

$$ga+\frac{p_1}{\rho}+\tfrac{1}{2}v^2\left(1-\frac{2\pi}{\lambda}b\right)^2=-ga+\frac{p_2}{\rho}+\tfrac{1}{2}v^2\left(1+\frac{2\pi}{\lambda}b\right)^2,$$

$$2ga+\frac{p_1-p_2}{\rho}=\frac{4\pi v^2 b}{\lambda}\,. \quad \text{.............................(i)}$$

At e the oscillatory horizontal velocity is zero, being half-way

between two points d and f of maximum velocity, and the vertical velocity is the maximum value of

$$\frac{dy}{dt}=\frac{2\pi}{T}\,a\cos 2\pi\frac{t}{T},$$

which is $$\frac{2\pi}{T}a \quad \text{or} \quad \frac{2\pi}{\lambda}va.$$

If V_3 is the resultant velocity at e, then since v and $\frac{dy}{dt}$ are at right angles to each other,

$$V_3{}^2=v^2+\frac{4\pi^2v^2}{\lambda^2}a^2.$$

Also $$h=0 \quad \text{and} \quad p=p_3,$$

so that applying Bernoulli's equation to the points d and e,

$$ga+\frac{p_1}{\rho}+\tfrac{1}{2}V_1{}^2=0+\frac{p_3}{\rho}+\tfrac{1}{2}V_3{}^2,$$

$$ga+\frac{p_1}{\rho}+\tfrac{1}{2}v^2\left(1-\frac{2\pi}{\lambda}b\right)^2=\frac{p_3}{\rho}+\tfrac{1}{2}v^2+\frac{1}{2}\frac{4\pi^2v^2a^2}{\lambda^2},$$

$$ga+\frac{p_1-p_3}{\rho}=\frac{2\pi v^2}{\lambda}b-\frac{1}{2}\frac{4\pi^2v^2b^2}{\lambda^2}+\frac{1}{2}\frac{4\pi^2v^2a^2}{\lambda^2}\ .\ \ldots\ldots\ldots\ldots\text{(ii)}$$

Multiplying by 2,

$$2ga+\frac{2(p_1-p_3)}{\rho}=\frac{4\pi v^2b}{\lambda}+\frac{4\pi^2v^2}{\lambda^2}(b^2-a^2).$$

On subtracting this from equation (i),

$$\frac{p_1-p_2-2p_1+2p_3}{\rho}=\frac{4\pi^2v^2}{\lambda^2}(a^2-b^2),$$

$$\frac{2p_3-(p_1+p_2)}{\rho}=\frac{4\pi^2v^2}{\lambda^2}(a^2-b^2).$$

The pressures p_1, p_2 and p_3 may be very small, but in any case p_3 is the mean of p_1 and p_2, so that the left-hand side of the equation is zero. Hence it follows that $a=b$, and the vertical and horizontal amplitudes of a particle are equal. This means that the particles describe circles (p. 105).

Three layers in a liquid are drawn in Fig. 216, and the positions of the particles are shown for a given instant. Since the wave travels from left to right, each circle is in an earlier phase than the one on

its left. If now the circles rotate as shown until every circle has made a complete rotation, the crest at A will travel to B. It will

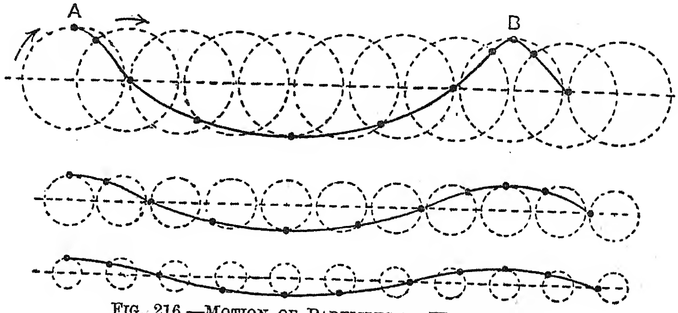


FIG. 216.—MOTION OF PARTICLES IN WATER WAVE.

be seen that the waves are not simple harmonic, although if the amplitude is small the departure from the simple harmonic form is slight.

Velocity of propagation.—In order to find the velocity of propagation v of the wave, put $b=a$ in equation (ii);

then
$$ga+\frac{p_1-p_3}{\rho}=\frac{2\pi v^2}{\lambda}a,$$

$$v^2=\frac{(p_1-p_3)+\rho ga}{\rho\cdot\frac{2\pi a}{\lambda}}.$$

At the surface of the liquid, the equation is as valid as for any other part, but the difference of pressure between D and F (Fig. 215) can only be due to the surface tension of the liquid, since the liquid is in contact with the atmosphere at both places. If the waves are so large that the curvature is negligible, the surface tension may be ignored and

$$v=\sqrt{\frac{g\lambda}{2\pi}},$$

which is the velocity of deep-sea waves.

Again, the curvature at E (Fig. 215) is zero, so that $p_3=0$;

$$\therefore\ v^2=\frac{p+\rho ga}{\rho\cdot\frac{2\pi a}{\lambda}},$$

where p is the pressure just under the surface at D, due to surface tension.

If the amplitude a is comparatively small with respect to the wave-length, the curvature at D is practically the same for all harmonic waves, and if the simple harmonic form is taken, the equation of the line CDE, etc., is $y = a \sin 2\pi \frac{x}{\lambda}$. Now

$$\frac{dy}{dx} = \frac{2\pi}{\lambda} a \cos 2\pi \frac{x}{\lambda} \quad \text{and} \quad \frac{d^2y}{dx^2} = -\left(\frac{2\pi}{\lambda}\right)^2 a \sin 2\pi \frac{x}{\lambda},$$

and the maximum value of this is $\left(\frac{2\pi}{\lambda}\right)^2 a$. On p. 146 it was seen that when the curvature is not great, its value is $\frac{d^2y}{dx^2}$, or the radius of curvature, $r = \frac{1}{\frac{d^2y}{dx^2}}$. Now the pressure due to surface tension is $\frac{T}{r}$ (p. 255), that is, $T\left(\frac{2\pi}{\lambda}\right)^2 a$, in which case the expression for v becomes

$$v^2 = \frac{T\left(\frac{2\pi}{\lambda}\right)^2 a + \rho g a}{\rho \cdot \frac{2\pi a}{\lambda}}$$

$$= \frac{2\pi T}{\rho\lambda} + \frac{g\lambda}{2\pi}.$$

If the waves are so small that the propagation is almost entirely due to surface tension, the term $g\lambda$ may be neglected, and

$$v = \sqrt{\frac{2\pi T}{\rho\lambda}}.$$

Relation between amplitude and depth.—In order to find how the amplitude a changes with depth below the surface, refer again to Fig. 215 and consider the stream-tube whose upper layer is *cdefgh*. If the rate of change of a with depth h is $\frac{da}{dh}$, then if the thickness of the tube in its undisplaced condition is δ, the difference of displacement between the upper and lower surfaces at d is $-\frac{da}{dh}\delta$, and $\delta - \frac{da}{dh}\delta$ the actual area of the tube, remembering that it has unit

thickness perpendicular to the plane of the diagram and that $\frac{da}{dh}$ is negative. Also at f the area is $\delta+\frac{da}{dh}\delta$. Now from the principle of continuity (p. 205) the product of velocity and area is constant for any tube;

$$\therefore\ V_1\left(\delta-\frac{da}{dh}\delta\right)=V_2\left(\delta+\frac{da}{dh}\delta\right);$$

$$\therefore\ V_1-V_2=(V_1+V_2)\frac{da}{dh}.$$

But
$$V_1=v-\frac{2\pi v}{\lambda}a \quad \text{and} \quad V_2=v+\frac{2\pi v}{\lambda}a;$$

$$\therefore\ V_1-V_2=-\frac{4\pi v}{\lambda}a \quad \text{and} \quad V_1+V_2=2v.$$

Then
$$-\frac{4\pi v}{\lambda}a=2v\frac{da}{dh},$$

$$dh=-\frac{\lambda}{2\pi}\frac{da}{a},$$

$$h=-\frac{\lambda}{2\pi}\log a+\mathrm{C},$$

where C is any constant. Let a_0 be the amplitude at the surface, where $h=0$. Then

$$h=-\frac{\lambda}{2\pi}\log\frac{a}{a_0},$$

$$\log\frac{a}{a_0}=-\frac{2\pi h}{\lambda},$$

$$a=a_0\epsilon^{-2\pi h/\lambda}.$$

That is, the amplitude falls off exponentially with the depth. If $h=\lambda$, $a=a_0\epsilon^{-2\pi}=0{\cdot}00186a_0$. Thus at a depth of a wave-length the amplitude has fallen to roughly 0·2 per cent. of the surface amplitude, and the decrease for the next wave-length in depth is at the same rate.

Minimum velocity.—It will be seen that the expression for v^2 on p. 311 will be smallest for some particular value of λ. The minimum value of v^2 may be found by differentiation with respect to λ:

$$v^2=\frac{2\pi T}{\rho\lambda}+\frac{g\lambda}{2\pi},$$

$$\frac{dv^2}{d\lambda}=-\frac{2\pi T}{\rho\lambda^2}+\frac{g}{2\pi};$$

equating this to zero,

$$\frac{g}{2\pi}=\frac{2\pi T}{\rho\lambda^2}, \quad \text{or} \quad \frac{g\lambda}{2\pi}=\frac{2\pi T}{\rho\lambda},$$

$$\lambda^2=\frac{4\pi^2 T}{\rho g}.$$

This value might correspond to a maximum or a minimum of v^2. In order to decide, differentiate again,

$$\frac{d^2v^2}{d\lambda^2}=+\frac{4\pi T}{\rho\lambda^3}.$$

Since every term here is positive, $\frac{d^2v^2}{d\lambda^2}$ is positive, and the value for λ found above corresponds therefore to a minimum of v^2.

In the case of water, $T=74$ dyne cm.$^{-1}$, $\rho=1$ gm. cm.$^{-3}$, and $g=981$ cm. sec.$^{-2}$;

$$\therefore\ \lambda=2\pi\sqrt{\tfrac{74}{981}}=1{\cdot}726 \text{ cm.},$$

and putting this value in the expression,

$$v^2=\frac{2\pi T}{\rho\lambda}+\frac{g\lambda}{2\pi},$$

$$v=23{\cdot}19 \text{ cm. sec.}^{-1}.$$

This is the smallest velocity that waves on the surface of water can have. For smaller wave-length, the surface tension term predominates and velocity increases with decreasing wave-length. For large wave-length, the gravitational term predominates and the velocity increases with increasing wave-length. For wave-lengths below that corresponding to minimum velocity, the disturbances are usually called ripples.

It is interesting to note that at the minimum velocity

$$\frac{2\pi T}{\rho\lambda}=\frac{g\lambda}{2\pi};$$

that is, the surface tension effect and the gravitational effect contribute equally to the value of v^2.

The late Lord Rayleigh used the measurement of the wave-length of ripples for determining the surface tension of the liquid. A glass plate dips into the liquid, and is rapidly raised and lowered by being attached to the prong of a tuning fork of known frequency. The surface of the liquid is illuminated intermittently with the same frequency as the fork. Under these conditions the ripples appear to stand still, and their wave-length can be measured.

Then
$$v^2=\frac{2\pi T}{\lambda\rho}+\frac{g\lambda}{2\pi},$$

and $v=n\lambda$, where n is the frequency;

$$\therefore\ T=\frac{\rho n^2\lambda^3}{2\pi}-\frac{g\rho\lambda^2}{4\pi^2}.$$

For fairly high frequencies $\frac{g\rho\lambda^2}{4\pi^2}$ may be neglected in comparison with the first term, so that

$$T=\frac{\rho n^2\lambda^3}{2\pi}.$$

Ripples in front of moving body.—An interesting example of the dependence of velocity on wave-length is exhibited in the production of steady ripples in front of a partly submerged object moving through water. Such a phenomenon occurs in front of the bow of a boat or when a stream flows past a fixed post. These two cases are the same, because it is the relative velocity of the water and the obstacle that matters. The movement of the water causes a heaping up against the fixed obstacle, as at A, Fig. 217. This causes a concavity at B, which will produce lowering of the pressure under the surface, due to surface tension, and a wave is started in the opposite direction to the stream. Since the water in contact with the obstacle is at rest, the ripple moves away from it; that is, up-stream. On proceeding from the obstacle, the water gradually increases in velocity until at a distance it reaches the main-stream velocity. When a place is reached where the velocity of the stream equals the velocity of the ripple, the ripple is stationary. Thus there is a fixed wave pattern in front of the obstacle. If the water is at rest and the solid body moving, the problem may be reduced to the above by imagining a velocity equal and opposite to the body to be superimposed on both.

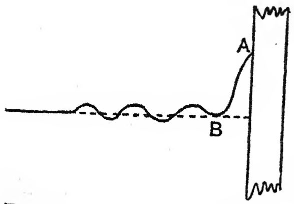


FIG. 217.—RIPPLES IN FRONT OF MOVING BODY.

The greater the velocity the sharper is the heaping up of the water and the shorter the wave-length of the ripple produced. This again means a greater velocity of the ripple, so that at a greater distance a velocity equal to the water is reached. If the velocity of the water is less than 23 cm. sec.$^{-1}$ there is no possible velocity of ripple corresponding to it, and no stationary ripples will be formed.

Beats.—There are several important phenomena that may occur when two trains of harmonic waves of nearly equal frequency have the same direction. If the velocity is independent of the frequency, as in the case of sound waves, the two waves compound in a manner that gives rise to beats. For example, if two tuning forks of nearly the same frequency are sounded together, the ear will hear a regular pulsation or throbbing superimposed on the note.

If the difference in wave-length of the waves is $d\lambda$, and the difference in periodic time dT, one wave may be represented by

$$y=a\sin 2\pi\left(\frac{x}{\lambda-\frac{1}{2}d\lambda}-\frac{t}{T-\frac{1}{2}dT}\right),$$

and the other by

$$y=a\sin 2\pi\left(\frac{x}{\lambda+\frac{1}{2}d\lambda}-\frac{t}{T+\frac{1}{2}dT}\right),$$

where λ and T are the mean wave-length and periodic time.

The resultant of these two is represented by

$$\begin{aligned} y&=a\sin 2\pi\left(\frac{x}{\lambda-\frac{1}{2}d\lambda}-\frac{t}{T-\frac{1}{2}dT}\right)+a\sin 2\pi\left(\frac{x}{\lambda+\frac{1}{2}d\lambda}-\frac{t}{T+\frac{1}{2}dT}\right)\\ &=2a\sin 2\pi\left(\frac{x\lambda}{\lambda^2-\frac{1}{4}(d\lambda)^2}-\frac{tT}{T^2-\frac{1}{4}(dT)^2}\right)\\ &\qquad\times\cos 2\pi\left(\frac{1}{2}\,\frac{x\,d\lambda}{\lambda^2-\frac{1}{4}(d\lambda)^2}-\frac{1}{2}\,\frac{t\,dT}{T^2-\frac{1}{4}(dT)^2}\right). \end{aligned}$$

If $d\lambda$ and dT are small, $(d\lambda)^2$ and $(dT)^2$ are of a second order of smallness and will be neglected;

$$\therefore\ y=2a\sin 2\pi\left(\frac{x}{\lambda}-\frac{t}{T}\right)\cos 2\pi\left(\frac{x\,d\lambda}{2\lambda^2}-\frac{t\,dT}{2T^2}\right).$$

This may be looked upon as a wave

$$\sin 2\pi\left(\frac{x}{\lambda}-\frac{t}{T}\right)$$

of mean wave-length λ, which has an amplitude

$$2a\cos 2\pi\left(\frac{x\,d\lambda}{2\lambda^2}-\frac{t\,dT}{2T^2}\right).$$

This amplitude also travels with velocity

$$\frac{\lambda^2}{d\lambda}\cdot\frac{dT}{T^2}=\frac{\lambda^2}{T^2}\cdot\frac{dT}{d\lambda}.$$

But $\lambda = vT$, or $d\lambda = v\,dT$, if v is constant, or $\dfrac{dT}{d\lambda} = \dfrac{1}{v}$;

$$\therefore \frac{\lambda^2}{T^2} \cdot \frac{dT}{d\lambda} = v^2 . \frac{1}{v} = v.$$

That is, the condition of amplitude travels with the same velocity as the constituent waves.

The distribution of amplitude at any instant, say $t = 0$, is

$$2a \cos 2\pi . \frac{x\,d\lambda}{2\lambda^2}.$$

If the frequency is n,

$$n = \frac{v}{\lambda} \quad \text{and} \quad \frac{dn}{d\lambda} = -\frac{v}{\lambda^2} \quad \text{or} \quad \frac{d\lambda}{\lambda^2} = -\frac{dn}{v};$$

$$\therefore\ 2a \cos 2\pi \frac{x\,d\lambda}{2\lambda^2} = 2a \cos 2\pi \frac{x\,dn}{2v}.$$

This is numerically equal to $2a$ when

$$\frac{2\pi x\,dn}{2v} = 0,\ \pi,\ 2\pi,\ 3\pi, \text{ etc., or } x = 0,\ \frac{v}{dn},\ \frac{2v}{dn},\ \frac{3v}{dn}, \text{ etc.,}$$

and equals zero when

$$\frac{2\pi x\,dn}{2v} = \frac{\pi}{2},\ \frac{3\pi}{2},\ \frac{5\pi}{2}, \text{ etc., or } x = \frac{v}{2\,dn},\ \frac{3v}{2\,dn},\ \frac{5v}{2\,dn}, \text{ etc.};$$

that is, points of maximum amplitude are separated by a distance $\dfrac{v}{dn}$, as are points of zero amplitude. If the difference in frequency dn of the constituent waves is unity, $x = v$, which means that in the path traversed in one second there is one maximum of amplitude. Similarly, if $dn = 2$ there are two maxima, and so on. Thus the **number of beats per second is the difference in the frequencies of the two constituent waves.**

In a similar manner, if a fixed point, say $x = 0$, is taken, the amplitude of the particle at this point is

$$2a \cos 2\pi \left(-\frac{t\,dT}{2T^2} \right) = 2a \cos 2\pi \frac{t\,dn}{2},$$

since

$$n = \frac{1}{T} \quad \text{and} \quad \frac{dn}{dT} = -\frac{1}{T^2}.$$

The amplitude equals $2a$ when

$$\pi t\,dn = 0,\ \pi,\ 2\pi, \text{ etc., or } t = 0,\ \frac{1}{dn},\ \frac{2}{dn}, \text{ etc.}$$

That is, the time between consecutive maxima is $\frac{1}{dn}$, and there are consequently dn maxima per second.

In Fig. 218 this effect is illustrated, but the constituent frequencies are much smaller than would be used in practice. In (*a*) the distance AC represents $\frac{1}{2}v$, so that in the whole distance v there would be respectively 12 and 10 wave-lengths, and in (*b*) the resultant at a given instant is drawn. At A and C the waves are assisting each other, and at B they are in opposite phases, giving zero resultant. If AC is half the velocity or the distance travelled in half a second,

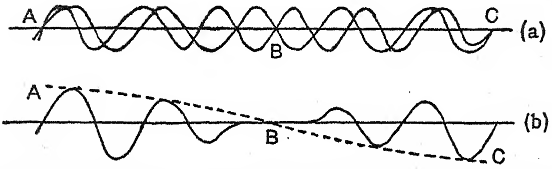


FIG. 218.—RESULTANT OF TWO WAVES OF NEARLY EQUAL WAVE-LENGTH.

then one maximum and one minimum per half second will pass any fixed point. Thus there will be two maxima and two minima passing per second, or there are two beats per second. This is in accordance with the statement that the number of beats per second is the difference in the frequencies of the constituent waves. Also the curve shown in dotted line in (*b*), which passes through the tips of the resultant wave-crests and hollows, is the curve

$$2a \cos 2\pi \frac{x\,d\lambda}{2\lambda^2},$$

obtained above (see p. 316).

Group velocity.—In the last case, the velocity has been considered to be independent of the wave-length, and the compound wave has maxima at A and C (Fig. 218 (*b*)), which travel with the common velocity of the constituent waves. In some cases the velocity is not independent of the wave-length, as in waves on the surface of water, and light travelling in a transparent medium other than empty space. If λ_1, λ_2 and T_1, T_2 are the respective wave-lengths and periodic times, the equation of one wave may be written

$$y_1 = a \sin 2\pi\left(\frac{x}{\lambda_1} - \frac{t}{T_1}\right),$$

and of the other

$$y_2 = a \sin 2\pi\left(\frac{x}{\lambda_2} - \frac{t}{T_2}\right).$$

The resultant is

$$y = y_1 + y_2 = a \sin 2\pi\left(\frac{x}{\lambda_1} - \frac{t}{T_1}\right) + a \sin 2\pi\left(\frac{x}{\lambda_2} - \frac{t}{T_2}\right)$$

$$= 2a \sin 2\pi\left\{\frac{x}{2}\left(\frac{1}{\lambda_1} + \frac{1}{\lambda_2}\right) - \frac{t}{2}\left(\frac{1}{T_1} + \frac{1}{T_2}\right)\right\}$$

$$\times \cos 2\pi\left\{\frac{x}{2}\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right) - \frac{t}{2}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right\}.$$

If λ_1 and λ_2 differ by a very small amount, the equation may be written

$$y = 2a \sin 2\pi\left(\frac{x}{\lambda} - \frac{t}{T}\right) \cos 2\pi\left\{\frac{x}{2} d\left(\frac{1}{\lambda}\right) - \frac{t}{2} d\left(\frac{1}{T}\right)\right\}.$$

This is a wave of mean velocity $v = \frac{\lambda}{T}$, whose amplitude

$$2a \cos 2\pi\left\{\frac{x}{2} d\left(\frac{1}{\lambda}\right) - \frac{t}{2} d\left(\frac{1}{T}\right)\right\}$$

has velocity $\dfrac{d\left(\frac{1}{T}\right)}{d\left(\frac{1}{\lambda}\right)}$. The quantity $\frac{\lambda}{t}$ is generally called the phase velocity and $\dfrac{d\left(\frac{1}{T}\right)}{d\left(\frac{1}{\lambda}\right)}$ the group velocity (v'). In Fig. 219 (a) two constituent waves are drawn, and in (b) the resultant wave at a given instant is represented by the full line. Any given wavelet, such as EFG, travels with the phase velocity v or $\frac{\lambda}{T}$. The dotted-line curve ABC, which represents the amplitudes at different points, is the curve

$$2a \cos 2\pi\left\{\frac{x}{2} d\left(\frac{1}{\lambda}\right) - \frac{t}{2} d\left(\frac{1}{T}\right)\right\},$$

whose velocity is no longer v, but is $v' = \dfrac{d\left(\frac{1}{T}\right)}{d\left(\frac{1}{\lambda}\right)}$, the group velocity.

The wavelets between two consecutive points of zero amplitude LM constitute a group. The number of groups passing any fixed

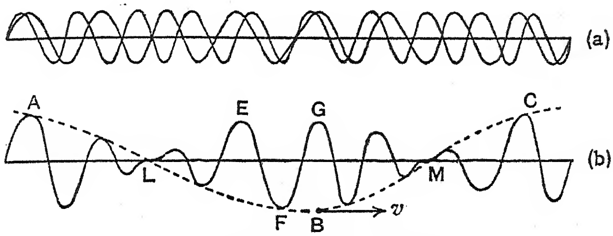


FIG. 219.—ILLUSTRATION OF GROUP VELOCITY.

point in space in a second may be found by taking a fixed point such as $x=0$ and noting that the amplitude is then given by

$$2a \cos 2\pi \left\{ -\frac{t}{2} d\left(\frac{1}{T}\right) \right\} = 2a \cos \pi t\, d\left(\frac{1}{T}\right).$$

This is zero when

$$\pi t\, d\left(\frac{1}{T}\right) = \frac{\pi}{2}, \frac{3\pi}{2}, \frac{5\pi}{2}, \text{ etc.,}$$

or when

$$t = \frac{1}{2d\left(\frac{1}{T}\right)}, \frac{3}{2d\left(\frac{1}{T}\right)}, \text{ etc.}$$

The interval between points on the wave, such as L and M, passing the chosen fixed point is thus

$$\frac{1}{d\left(\frac{1}{T}\right)}, \quad \text{or} \quad \frac{1}{\frac{1}{T_1} - \frac{1}{T_2}}.$$

Now if n_1 and n_2 are the frequencies of the constituent waves,

$$n_1 = \frac{1}{T_1} \quad \text{and} \quad n_2 = \frac{1}{T_2},$$

so that the time taken for a group to pass a fixed point is

$$\frac{1}{n_1 - n_2}.$$

The number of groups passing per second is therefore $n_1 - n_2$, or the difference in the frequencies of the two waves.

Group velocity of waves on water.—For waves on deep water when surface tension effects can be neglected and the propagation is entirely due to gravity, the velocity is $\sqrt{\frac{g\lambda}{2\pi}}$ (p. 310). Thus

$$\frac{\lambda}{T}=\sqrt{\frac{g\lambda}{2\pi}}=v,$$

$$\frac{\lambda}{T^2}=\frac{g}{2\pi},$$

$$\frac{1}{\lambda}=\frac{2\pi}{g}\cdot\left(\frac{1}{T}\right)^2;$$

$$\therefore \quad \frac{d\left(\frac{1}{\lambda}\right)}{d\left(\frac{1}{T}\right)}=2\cdot\frac{2\pi}{g}\cdot\frac{1}{T}=2\cdot\frac{2\pi}{g\lambda}\cdot\frac{\lambda}{T}=2\cdot\frac{1}{v^2}\cdot v=\frac{2}{v}.$$

$$\therefore \text{ group velocity } \frac{d\left(\frac{1}{T}\right)}{d\left(\frac{1}{\lambda}\right)}=\frac{v}{2}.$$

That is, the group velocity is half the phase velocity.

In the case of ripples of wave-length small enough for the effect of gravity to be neglected, $v=\sqrt{\frac{2\pi S}{\lambda\rho}}$ (p. 311), where S is the surface tension and ρ the density. The surface tension is here written S to avoid confusion with the periodic time.

Then,
$$\frac{\lambda^2}{T^2}=\frac{2\pi S}{\lambda\rho} \quad \text{or} \quad \frac{1}{T^2}=\frac{2\pi S}{\rho}\cdot\left(\frac{1}{\lambda}\right)^3,$$

that is,
$$\frac{1}{T}=\sqrt{\frac{2\pi S}{\rho}}\left(\frac{1}{\lambda}\right)^{\frac{3}{2}};$$

and
$$\text{group velocity}=\frac{d\left(\frac{1}{T}\right)}{d\left(\frac{1}{\lambda}\right)}=\frac{3}{2}\sqrt{\frac{2\pi S}{\rho}}\cdot\left(\frac{1}{\lambda}\right)^{\frac{1}{2}}$$
$$=\frac{3}{2}\sqrt{\frac{2\pi S}{\lambda\rho}}$$
$$=\tfrac{3}{2}v.$$

That is, the group velocity is 3/2 times the phase velocity.

Waves formed by moving body.—A solid body moving through any medium produces a disturbance which travels from it in the form of waves. If the velocity is independent of the wave-length, the group velocity is equal to the phase velocity. This is the case for air waves (p. 299). If then a bullet has such a velocity that it produces a compression in front of it, the wave group travels outwards with the common wave velocity. When the nose of the bullet is at A (Fig. 220) the compression wave starts outwards and travels as a spherical compression of velocity v. After an interval of time t let the wave have reached a sphere C whose radius is vt. The bullet

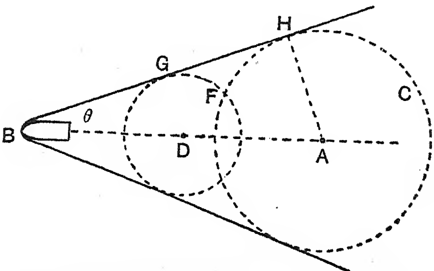


FIG. 220.—WAVES FORMED BY BULLET IN AIR.

has now reached B where $AB = Vt$, V being the velocity of the bullet. After time $\frac{t}{2}$ the bullet is at D, and at the end of t sec. the wave which started at time $\frac{t}{2}$ sec. has become the spherical wave F, where $DF = v \cdot \frac{t}{2}$, and $BD = V\frac{t}{2}$. From geometry it will be seen that a cone BGH will touch all such spheres, and this cone is the shape of the compression wave when the bullet is at B.

If θ is the angle ABH,

$$\sin\theta = \frac{AH}{AB} = \frac{v}{V}.$$

By observing such compression waves by means of the shadow they produced when illuminated for an instant, C. V. Boys measured the velocities of bullets fired from a rifle.

The long waves made by a ship moving through water are not so simple as the above. The velocity of these long waves is not independent of the wave-length, and the group velocity is $\frac{v}{2}$ (p. 320). As it is the group that is observable and not the constituent waves,

the matter is more complicated than in the case of an air wave. As the ship passes A (Fig. 221) the water is heaped up at the bow, and if the group velocity were equal to the wave velocity v, the wave would have reached C when the bow is at B, where $\frac{AC}{AB}=\frac{v}{V}$. But as the bow passes any point, the water subsides, the crest forming a hollow,

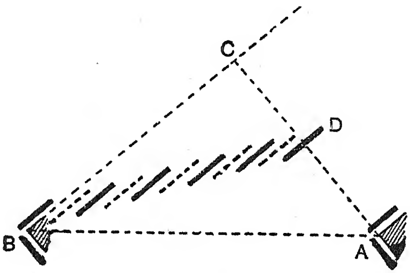


FIG. 221.—WATER WAVES AT BOW OF BOAT.

which again forms a crest, but with slightly changed period and wave-length. The group velocity is thus $\frac{v}{2}$, and the group has reached D when the bow reaches B, where $AD=\frac{1}{2}AC$.

The track of the group is therefore from B to D, but it is not continuous, like the track BH in Fig. 220. As the bow passes, the crest E (Fig. 222 (a)) subsides, and the crest which left at G and has

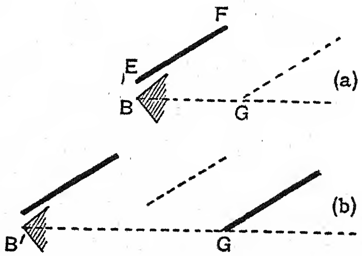


FIG. 222.—PRODUCTION OF WAVES AT BOW OF BOAT.

reached F has become a hollow at G, which travels outwards, to be in turn followed by a crest at G (Fig. 222 (b)). So long as the oscillations last, successive waves are sent out, and the result is a series of crests and hollows in the line BD (Fig. 221). Such a series

of waves can always be seen when a body, large enough to produce gravitational waves, passes along the surface of water.

Exercises on Chapter XIII

1. Define wave motion and show that it can be represented by a simple equation involving the velocity of propagation.

2. Give the equation of a simple harmonic wave in terms of wave-length and periodic time. Find an expression for the particle velocity in such a case.

3. Distinguish between a transverse wave and a longitudinal wave, giving examples of each.

4. Show how a longitudinal wave may be represented by means of a sine curve. Find the value for the compression in such a wave.

5. Find an expression for the velocity of a compression wave in air. What value of the elasticity should be used in calculating the velocity of the wave from this expression ?

6. Define the term "interference." Show that two simple harmonic waves of the same amplitude and frequency travelling in opposite directions compound into a steady state of vibration.

7. Describe the meaning of the term "beats," and show that the frequency of the beats is the difference of the frequencies of the constituent waves.

8. Explain group velocity, and calculate its value when

$$v=\sqrt{\frac{g\lambda}{2\pi}} \text{ and when } v=\sqrt{\frac{2\pi S}{\lambda\rho}}.$$

8. Contrast the meaning of *longitudinal progressive wave* and *transverse stationary wave*.

Write down the equation of a simple harmonic progressive wave of amplitude 0·1 mm. and frequency 100 vibrations per sec. travelling in the positive direction of the axis of x with a velocity of 33,000 cm. per sec. Explain the equation. Lond. Int. Sci.

	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
10	0000	0043	0086	0128	0170						4	9	13	17	21	26	30	34	38
						0212	0253	0294	0334	0374	4	8	12	16	20	24	28	32	36
11	0414	0453	0492	0531	0569						4	8	12	15	19	23	27	31	35
						0607	0645	0682	0719	0755	4	7	11	15	19	22	26	30	33
12	0792	0828	0864	0899	0934						3	7	11	14	18	21	25	28	32
						0969	1004	1038	1072	1106	3	7	10	14	17	20	24	27	31
13	1139	1173	1206	1239	1271						3	7	10	13	16	20	23	26	30
						1303	1335	1367	1399	1430	3	7	10	13	16	19	22	25	29
14	1461	1492	1523	1553	1584						3	6	9	12	15	19	22	25	28
						1614	1644	1673	1703	1732	3	6	9	12	15	17	20	23	26
15	1761	1790	1818	1847	1875						3	6	9	11	14	17	20	23	26
						1903	1931	1959	1987	2014	3	6	8	11	14	17	19	22	25
16	2041	2068	2095	2122	2148						3	5	8	11	14	16	19	22	24
						2175	2201	2227	2253	2279	3	5	8	10	13	16	18	21	23
17	2304	2330	2355	2380	2405						3	5	8	10	13	15	18	20	23
						2430	2455	2480	2504	2529	2	5	7	10	12	15	17	20	22
18	2553	2577	2601	2625	2648						2	5	7	9	12	14	16	19	21
						2672	2695	2718	2742	2765	2	5	7	9	11	14	16	18	21
19	2788	2810	2833	2856	2878						2	4	7	9	11	13	16	18	20
						2900	2923	2945	2967	2989	2	4	6	8	11	13	15	17	19
20	3010	3032	3054	3075	3096	3118	3139	3160	3181	3201	2	4	6	8	11	13	15	17	19
21	3222	3243	3263	3284	3304	3324	3345	3365	3385	3404	2	4	6	8	10	12	14	16	18
22	3424	3444	3464	3483	3502	3522	3541	3560	3579	3598	2	4	6	8	10	12	14	15	17
23	3617	3636	3655	3674	3692	3711	3729	3747	3766	3784	2	4	6	7	9	11	13	15	17
24	3802	3820	3838	3856	3874	3892	3909	3927	3945	3962	2	4	5	7	9	11	12	14	16
25	3979	3997	4014	4031	4048	4065	4082	4099	4116	4133	2	3	5	7	9	10	12	14	15
26	4150	4166	4183	4200	4216	4232	4249	4265	4281	4298	2	3	5	7	8	10	11	13	15
27	4314	4330	4346	4362	4378	4393	4409	4425	4440	4456	2	3	5	6	8	9	11	13	14
28	4472	4487	4502	4518	4533	4548	4564	4579	4594	4609	2	3	5	6	8	9	11	12	14
29	4624	4639	4654	4669	4683	4698	4713	4728	4742	4757	1	3	4	6	7	9	10	12	13
30	4771	4786	4800	4814	4829	4843	4857	4871	4886	4900	1	3	4	6	7	9	10	11	13
31	4914	4928	4942	4955	4969	4983	4997	5011	5024	5038	1	3	4	6	7	8	10	11	12
32	5051	5065	5079	5092	5105	5119	5132	5145	5159	5172	1	3	4	5	7	8	9	11	12
33	5185	5198	5211	5224	5237	5250	5263	5276	5289	5302	1	3	4	5	6	8	9	10	12
34	5315	5328	5340	5353	5366	5378	5391	5403	5416	5428	1	3	4	5	6	8	9	10	11
35	5441	5453	5465	5478	5490	5502	5514	5527	5539	5551	1	2	4	5	6	7	9	10	11
36	5563	5575	5587	5599	5611	5623	5635	5647	5658	5670	1	2	4	5	6	7	8	10	11
37	5682	5694	5705	5717	5729	5740	5752	5763	5775	5786	1	2	3	5	6	7	8	9	10
38	5798	5809	5821	5832	5843	5855	5866	5877	5888	5899	1	2	3	5	6	7	8	9	10
39	5911	5922	5933	5944	5955	5966	5977	5988	5999	6010	1	2	3	4	5	7	8	9	10
40	6021	6031	6042	6053	6064	6075	6085	6096	6107	6117	1	2	3	4	5	6	8	9	10
41	6128	6138	6149	6160	6170	6180	6191	6201	6212	6222	1	2	3	4	5	6	7	8	9
42	6232	6243	6253	6263	6274	6284	6294	6304	6314	6325	1	2	3	4	5	6	7	8	9
43	6335	6345	6355	6365	6375	6385	6395	6405	6415	6425	1	2	3	4	5	6	7	8	9
44	6435	6444	6454	6464	6474	6484	6493	6503	6513	6522	1	2	3	4	5	6	7	8	9
45	6532	6542	6551	6561	6571	6580	6590	6599	6609	6618	1	2	3	4	5	6	7	8	9
46	6628	6637	6646	6656	6665	6675	6684	6693	6702	6712	1	2	3	4	5	6	7	7	8
47	6721	6730	6739	6749	6758	6767	6776	6785	6794	6803	1	2	3	4	5	5	6	7	8
48	6812	6821	6830	6839	6848	6857	6866	6875	6884	6893	1	2	3	4	4	5	6	7	8
49	6902	6911	6920	6928	6937	6946	6955	6964	6972	6981	1	2	3	4	4	5	6	7	8

	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
50	6990	6998	7007	7016	7024	7033	7042	7050	7059	7067	1	2	3	3	4	5	6	7	8
51	7076	7084	7093	7101	7110	7118	7126	7135	7143	7152	1	2	3	3	4	5	6	7	8
52	7160	7168	7177	7185	7193	7202	7210	7218	7226	7235	1	2	2	3	4	5	6	7	7
53	7243	7251	7259	7267	7275	7284	7292	7300	7308	7316	1	2	2	3	4	5	6	6	7
54	7324	7332	7340	7348	7356	7364	7372	7380	7388	7396	1	2	2	3	4	5	6	6	7
55	7404	7412	7419	7427	7435	7443	7451	7459	7466	7474	1	2	2	3	4	5	5	6	7
56	7482	7490	7497	7505	7513	7520	7528	7536	7543	7551	1	2	2	3	4	5	5	6	7
57	7559	7566	7574	7582	7589	7597	7604	7612	7619	7627	1	2	2	3	4	5	5	6	7
58	7634	7642	7649	7657	7664	7672	7679	7686	7694	7701	1	1	2	3	4	4	5	6	7
59	7709	7716	7723	7731	7738	7745	7752	7760	7767	7774	1	1	2	3	4	4	5	6	7
60	7782	7789	7796	7803	7810	7818	7825	7832	7839	7846	1	1	2	3	4	4	5	6	6
61	7853	7860	7868	7875	7882	7889	7896	7903	7910	7917	1	1	2	3	4	4	5	6	6
62	7924	7931	7938	7945	7952	7959	7966	7973	7980	7987	1	1	2	3	3	4	5	6	6
63	7993	8000	8007	8014	8021	8028	8035	8041	8048	8055	1	1	2	3	3	4	5	5	6
64	8062	8069	8075	8082	8089	8096	8102	8109	8116	8122	1	1	2	3	3	4	5	5	6
65	8129	8136	8142	8149	8156	8162	8169	8176	8182	8189	1	1	2	3	3	4	5	5	6
66	8195	8202	8209	8215	8222	8228	8235	8241	8248	8254	1	1	2	3	3	4	5	5	6
67	8261	8267	8274	8280	8287	8293	8299	8306	8312	8319	1	1	2	3	3	4	5	5	6
68	8325	8331	8338	8344	8351	8357	8363	8370	8376	8382	1	1	2	3	3	4	4	5	6
69	8388	8395	8401	8407	8414	8420	8426	8432	8439	8445	1	1	2	2	3	4	4	5	6
70	8451	8457	8463	8470	8476	8482	8488	8494	8500	8506	1	1	2	2	3	4	4	5	6
71	8513	8519	8525	8531	8537	8543	8549	8555	8561	8567	1	1	2	2	3	4	4	5	5
72	8573	8579	8585	8591	8597	8603	8609	8615	8621	8627	1	1	2	2	3	4	4	5	5
73	8633	8639	8645	8651	8657	8663	8669	8675	8681	8686	1	1	2	2	3	4	4	5	5
74	8692	8698	8704	8710	8716	8722	8727	8733	8739	8745	1	1	2	2	3	4	4	5	5
75	8751	8756	8762	8768	8774	8779	8785	8791	8797	8802	1	1	2	2	3	3	4	5	5
76	8808	8814	8820	8825	8831	8837	8842	8848	8854	8859	1	1	2	2	3	3	4	5	5
77	8865	8871	8876	8882	8887	8893	8899	8904	8910	8915	1	1	2	2	3	3	4	4	5
78	8921	8927	8932	8938	8943	8949	8954	8960	8965	8971	1	1	2	2	3	3	4	4	5
79	8976	8982	8987	8993	8998	9004	9009	9015	9020	9025	1	1	2	2	3	3	4	4	5
80	9031	9036	9042	9047	9053	9058	9063	9069	9074	9079	1	1	2	2	3	3	4	4	5
81	9085	9090	9096	9101	9106	9112	9117	9122	9128	9133	1	1	2	2	3	3	4	4	5
82	9138	9143	9149	9154	9159	9165	9170	9175	9180	9186	1	1	2	2	3	3	4	4	5
83	9191	9196	9201	9206	9212	9217	9222	9227	9232	9238	1	1	2	2	3	3	4	4	5
84	9243	9248	9253	9258	9263	9269	9274	9279	9284	9289	1	1	2	2	3	3	4	4	5
85	9294	9299	9304	9309	9315	9320	9325	9330	9335	9340	1	1	2	2	3	3	4	4	5
86	9345	9350	9355	9360	9365	9370	9375	9380	9385	9390	1	1	2	2	3	3	4	4	5
87	9395	9400	9405	9410	9415	9420	9425	9430	9435	9440	0	1	1	2	2	3	3	4	4
88	9445	9450	9455	9460	9465	9469	9474	9479	9484	9489	0	1	1	2	2	3	3	4	4
89	9494	9499	9504	9509	9513	9518	9523	9528	9533	9538	0	1	1	2	2	3	3	4	4
90	9542	9547	9552	9557	9562	9566	9571	9576	9581	9586	0	1	1	2	2	3	3	4	4
91	9590	9595	9600	9605	9609	9614	9619	9624	9628	9633	0	1	1	2	2	3	3	4	4
92	9638	9643	9647	9652	9657	9661	9666	9671	9675	9680	0	1	1	2	2	3	3	4	4
93	9685	9689	9694	9699	9703	9708	9713	9717	9722	9727	0	1	1	2	2	3	3	4	4
94	9731	9736	9741	9745	9750	9754	9759	9763	9768	9773	0	1	1	2	2	3	3	4	4
95	9777	9782	9786	9791	9795	9800	9805	9809	9814	9818	0	1	1	2	2	3	3	4	4
96	9823	9827	9832	9836	9841	9845	9850	9854	9859	9863	0	1	1	2	2	3	3	4	4
97	9868	9872	9877	9881	9886	9890	9894	9899	9903	9908	0	1	1	2	2	3	3	4	4
98	9912	9917	9921	9926	9930	9934	9939	9943	9948	9952	0	1	1	2	2	3	3	4	4
99	9956	9961	9965	9969	9974	9978	9983	9987	9991	9996	0	1	1	2	2	3	3	3	4

	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
·00	1000	1002	1005	1007	1009	1012	1014	1016	1019	1021	0	0	1	1	1	1	2	2	2
·01	1023	1026	1028	1030	1033	1035	1038	1040	1042	1045	0	0	1	1	1	1	2	2	2
·02	1047	1050	1052	1054	1057	1059	1062	1064	1067	1069	0	0	1	1	1	1	2	2	2
·03	1072	1074	1076	1079	1081	1084	1086	1089	1091	1094	0	0	1	1	1	1	2	2	2
·04	1096	1099	1102	1104	1107	1109	1112	1114	1117	1119	0	1	1	1	1	2	2	2	2
·05	1122	1125	1127	1130	1132	1135	1138	1140	1143	1146	0	1	1	1	1	2	2	2	2
·06	1148	1151	1153	1156	1159	1161	1164	1167	1169	1172	0	1	1	1	1	2	2	2	2
·07	1175	1178	1180	1183	1186	1189	1191	1194	1197	1199	0	1	1	1	1	2	2	2	2
·08	1202	1205	1208	1211	1213	1216	1219	1222	1225	1227	0	1	1	1	1	2	2	2	3
·09	1230	1233	1236	1239	1242	1245	1247	1250	1253	1256	0	1	1	1	1	2	2	2	3
·10	1259	1262	1265	1268	1271	1274	1276	1279	1282	1285	0	1	1	1	1	2	2	2	3
·11	1288	1291	1294	1297	1300	1303	1306	1309	1312	1315	0	1	1	1	2	2	2	2	3
·12	1318	1321	1324	1327	1330	1334	1337	1340	1343	1346	0	1	1	1	2	2	2	2	3
·13	1349	1352	1355	1358	1361	1365	1368	1371	1374	1377	0	1	1	1	2	2	2	3	3
·14	1380	1384	1387	1390	1393	1396	1400	1403	1406	1409	0	1	1	1	2	2	2	3	3
·15	1413	1416	1419	1422	1426	1429	1432	1435	1439	1442	0	1	1	1	2	2	2	3	3
·16	1445	1449	1452	1455	1459	1462	1466	1469	1472	1476	0	1	1	1	2	2	2	3	3
·17	1479	1483	1486	1489	1493	1496	1500	1503	1507	1510	0	1	1	1	2	2	2	3	3
·18	1514	1517	1521	1524	1528	1531	1535	1538	1542	1545	0	1	1	1	2	2	2	3	3
·19	1549	1552	1556	1560	1563	1567	1570	1574	1578	1581	0	1	1	1	2	2	3	3	3
·20	1585	1589	1592	1596	1600	1603	1607	1611	1614	1618	0	1	1	1	2	2	3	3	3
·21	1622	1626	1629	1633	1637	1641	1644	1648	1652	1656	0	1	1	2	2	2	3	3	3
·22	1660	1663	1667	1671	1675	1679	1683	1687	1690	1694	0	1	1	2	2	2	3	3	3
·23	1698	1702	1706	1710	1714	1718	1722	1726	1730	1734	0	1	1	2	2	2	3	3	4
·24	1738	1742	1746	1750	1754	1758	1762	1766	1770	1774	0	1	1	2	2	2	3	3	4
·25	1778	1782	1786	1791	1795	1799	1803	1807	1811	1816	0	1	1	2	2	2	3	3	4
·26	1820	1824	1828	1832	1837	1841	1845	1849	1854	1858	0	1	1	2	2	3	3	3	4
·27	1862	1866	1871	1875	1879	1884	1888	1892	1897	1901	0	1	1	2	2	3	3	3	4
·28	1905	1910	1914	1919	1923	1928	1932	1936	1941	1945	0	1	1	2	2	3	3	4	4
·29	1950	1954	1959	1963	1968	1972	1977	1982	1986	1991	0	1	1	2	2	3	3	4	4
·30	1995	2000	2004	2009	2014	2018	2023	2028	2032	2037	0	1	1	2	2	3	3	4	4
·31	2042	2046	2051	2056	2061	2065	2070	2075	2080	2084	0	1	1	2	2	3	3	4	4
·32	2089	2094	2099	2104	2109	2113	2118	2123	2128	2133	0	1	1	2	2	3	3	4	4
·33	2138	2143	2148	2153	2158	2163	2168	2173	2178	2183	0	1	1	2	2	3	3	4	4
·34	2188	2193	2198	2203	2208	2213	2218	2223	2228	2234	1	1	2	2	3	3	4	4	5
·35	2239	2244	2249	2254	2259	2265	2270	2275	2280	2286	1	1	2	2	3	3	4	4	5
·36	2291	2296	2301	2307	2312	2317	2323	2328	2333	2339	1	1	2	2	3	3	4	4	5
·37	2344	2350	2355	2360	2366	2371	2377	2382	2388	2393	1	1	2	2	3	3	4	4	5
·38	2399	2404	2410	2415	2421	2427	2432	2438	2443	2449	1	1	2	2	3	3	4	4	5
·39	2455	2460	2466	2472	2477	2483	2489	2495	2500	2506	1	1	2	2	3	3	4	5	5
·40	2512	2518	2523	2529	2535	2541	2547	2553	2559	2564	1	1	2	2	3	4	4	5	5
·41	2570	2576	2582	2588	2594	2600	2606	2612	2618	2624	1	1	2	2	3	4	4	5	5
·42	2630	2636	2642	2649	2655	2661	2667	2673	2679	2685	1	1	2	2	3	4	4	5	6
·43	2692	2698	2704	2710	2716	2723	2729	2735	2742	2748	1	1	2	3	3	4	4	5	6
·44	2754	2761	2767	2773	2780	2786	2793	2799	2805	2812	1	1	2	3	3	4	4	5	6
·45	2818	2825	2831	2838	2844	2851	2858	2864	2871	2877	1	1	2	3	3	4	5	5	6
·46	2884	2891	2897	2904	2911	2917	2924	2931	2938	2944	1	1	2	3	3	4	5	5	6
·47	2951	2958	2965	2972	2979	2985	2992	2999	3006	3013	1	1	2	3	3	4	5	5	6
·48	3020	3027	3034	3041	3048	3055	3062	3069	3076	3083	1	1	2	3	4	4	5	6	6
·49	3090	3097	3105	3112	3119	3126	3133	3141	3148	3155	1	1	2	3	4	4	5	6	6

	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
·50	3162	3170	3177	3184	3192	3199	3206	3214	3221	3228	1	1	2	3	4	4	5	6	7
·51	3236	3243	3251	3258	3266	3273	3281	3289	3296	3304	1	2	2	3	4	5	5	6	7
·52	3311	3319	3327	3334	3342	3350	3357	3365	3373	3381	1	2	2	3	4	5	5	6	7
·53	3388	3396	3404	3412	3420	3428	3436	3443	3451	3459	1	2	2	3	4	5	6	6	7
·54	3467	3475	3483	3491	3499	3508	3516	3524	3532	3540	1	2	2	3	4	5	6	6	7
·55	3548	3556	3565	3573	3581	3589	3597	3606	3614	3622	1	2	2	3	4	5	6	7	7
·56	3631	3639	3648	3656	3664	3673	3681	3690	3698	3707	1	2	3	3	4	5	6	7	8
·57	3715	3724	3733	3741	3750	3758	3767	3776	3784	3793	1	2	3	3	4	5	6	7	8
·58	3802	3811	3819	3828	3837	3846	3855	3864	3873	3882	1	2	3	4	4	5	6	7	8
·59	3890	3899	3908	3917	3926	3936	3945	3954	3963	3972	1	2	3	4	5	5	6	7	8
·60	3981	3990	3999	4009	4018	4027	4036	4046	4055	4064	1	2	3	4	5	6	6	7	8
·61	4074	4083	4093	4102	4111	4121	4130	4140	4150	4159	1	2	3	4	5	6	7	8	9
·62	4169	4178	4188	4198	4207	4217	4227	4236	4246	4256	1	2	3	4	5	6	7	8	9
·63	4266	4276	4285	4295	4305	4315	4325	4335	4345	4355	1	2	3	4	5	6	7	8	9
·64	4365	4375	4385	4395	4406	4416	4426	4436	4446	4457	1	2	3	4	5	6	7	8	9
·65	4467	4477	4487	4498	4508	4519	4529	4539	4550	4560	1	2	3	4	5	6	7	8	9
·66	4571	4581	4592	4603	4613	4624	4634	4645	4656	4667	1	2	3	4	5	6	7	9	10
·67	4677	4688	4699	4710	4721	4732	4742	4753	4764	4775	1	2	3	4	5	7	8	9	10
·68	4786	4797	4808	4819	4831	4842	4853	4864	4875	4887	1	2	3	4	6	7	8	9	10
·69	4898	4909	4920	4932	4943	4955	4966	4977	4989	5000	1	2	3	5	6	7	8	9	10
·70	5012	5023	5035	5047	5058	5070	5082	5093	5105	5117	1	2	4	5	6	7	8	9	11
·71	5129	5140	5152	5164	5176	5188	5200	5212	5224	5236	1	2	4	5	6	7	8	10	11
·72	5248	5260	5272	5284	5297	5309	5321	5333	5346	5358	1	2	4	5	6	7	9	10	11
·73	5370	5383	5395	5408	5420	5433	5445	5458	5470	5483	1	3	4	5	6	8	9	10	11
·74	5495	5508	5521	5534	5546	5559	5572	5585	5598	5610	1	3	4	5	6	8	9	10	12
·75	5623	5636	5649	5662	5675	5689	5702	5715	5728	5741	1	3	4	5	7	8	9	10	12
·76	5754	5768	5781	5794	5808	5821	5834	5848	5861	5875	1	3	4	5	7	8	9	11	12
·77	5888	5902	5916	5929	5943	5957	5970	5984	5998	6012	1	3	4	5	7	8	10	11	12
·78	6026	6039	6053	6067	6081	6095	6109	6124	6138	6152	1	3	4	6	7	8	10	11	13
·79	6166	6180	6194	6209	6223	6237	6252	6266	6281	6295	1	3	4	6	7	9	10	11	13
·80	6310	6324	6339	6353	6368	6383	6397	6412	6427	6442	1	3	4	6	7	9	10	12	13
·81	6457	6471	6486	6501	6516	6531	6546	6561	6577	6592	2	3	5	6	8	9	11	12	14
·82	6607	6622	6637	6653	6668	6683	6699	6714	6730	6745	2	3	5	6	8	9	11	12	14
·83	6761	6776	6792	6808	6823	6839	6855	6871	6887	6902	2	3	5	6	8	9	11	13	14
·84	6918	6934	6950	6966	6982	6998	7015	7031	7047	7063	2	3	5	6	8	10	11	13	15
·85	7079	7096	7112	7129	7145	7161	7178	7194	7211	7228	2	3	5	7	8	10	12	13	15
·86	7244	7261	7278	7295	7311	7328	7345	7362	7379	7396	2	3	5	7	8	10	12	13	15
·87	7413	7430	7447	7464	7482	7499	7516	7534	7551	7568	2	3	5	7	9	10	12	14	16
·88	7586	7603	7621	7638	7656	7674	7691	7709	7727	7745	2	4	5	7	9	11	12	14	16
·89	7762	7780	7798	7816	7834	7852	7870	7889	7907	7925	2	4	5	7	9	11	13	14	16
·90	7943	7962	7980	7998	8017	8035	8054	8072	8091	8110	2	4	6	7	9	11	13	15	17
·91	8128	8147	8166	8185	8204	8222	8241	8260	8279	8299	2	4	6	8	9	11	13	15	17
·92	8318	8337	8356	8375	8395	8414	8433	8453	8472	8492	2	4	6	8	10	12	14	15	17
·93	8511	8531	8551	8570	8590	8610	8630	8650	8670	8690	2	4	6	8	10	12	14	16	18
·94	8710	8730	8750	8770	8790	8810	8831	8851	8872	8892	2	4	6	8	10	12	14	16	18
·95	8913	8933	8954	8974	8995	9016	9036	9057	9078	9099	2	4	6	8	10	12	15	17	19
·96	9120	9141	9162	9183	9204	9226	9247	9268	9290	9311	2	4	6	8	11	13	15	17	19
·97	9333	9354	9376	9397	9419	9441	9462	9484	9506	9528	2	4	7	9	11	13	15	17	20
·98	9550	9572	9594	9616	9638	9661	9683	9705	9727	9750	2	4	7	9	11	13	16	18	20
·99	9772	9795	9817	9840	9863	9886	9908	9931	9954	9977	2	5	7	9	11	14	16	18	20

TRIGONOMETRICAL TABLE.

Angle.	Radians.	Sine.	Tangent.	Cotangent.	Cosine.		
0°	0	0	0	∞	1	1·5708	90°
1	·0175	·0175	·0175	57·2900	·9998	1·5533	89
2	·0349	·0349	·0349	28·6363	·9994	1·5359	88
3	·0524	·0523	·0524	19·0811	·9986	1·5184	87
4	0698	·0698	·0699	14·3006	·9976	1·5010	86
5	·0873	·0872	·0875	11·4301	·9962	1·4835	85
6	·1047	·1045	·1051	9·5144	·9945	1·4661	84
7	·1222	·1219	·1228	8·1443	·9925	1·4486	83
8	·1396	·1392	·1405	7·1154	·9903	1·4312	82
9	·1571	·1564	·1584	6·3138	·9877	1·4137	81
10	·1745	·1736	·1763	5·6713	·9848	1·3963	80
11	·1920	·1908	·1944	5·1446	·9816	1·3788	79
12	·2094	·2079	·2126	4·7046	·9781	1·3614	78
13	·2269	·2250	·2309	4·3315	·9744	1·3439	77
14	·2443	·2419	·2493	4·0108	·9703	1·3265	76
15	·2618	·2588	·2679	3·7321	·9659	1·3090	75
16	·2793	·2756	·2867	3·4874	·9613	1·2915	74
17	·2967	·2924	·3057	3·2709	·9563	1·2741	73
18	·3142	·3090	·3249	3·0777	·9511	1·2566	72
19	·3316	·3256	·3443	2·9042	·9455	1·2392	71
20	·3491	·3420	·3640	2·7475	·9397	1·2217	70
21	·3665	·3584	·3839	2·6051	·9336	1·2043	69
22	·3840	·3746	·4040	2·4751	·9272	1·1868	68
23	·4014	·3907	·4245	2·3559	·9205	1·1694	67
24	·4189	·4067	·4452	2·2460	·9135	1·1519	66
25	·4363	·4226	·4663	2·1445	·9063	1·1345	65
26	·4538	·4384	·4877	2·0503	·8988	1·1170	64
27	·4712	·4540	·5095	1·9626	·8910	1·0996	63
28	·4887	·4695	·5317	1·8807	·8830	1·0821	62
29	·5061	·4848	·5543	1·8040	·8746	1·0647	61
30	·5236	·5000	·5774	1·7321	·8660	1·0472	60
31	·5411	·5150	·6009	1·6643	·8572	1·0297	59
32	·5585	·5299	·6249	1·6003	·8480	1·0123	58
33	·5760	·5446	·6494	1·5399	·8387	·9948	57
34	·5934	·5592	·6745	1·4826	·8290	·9774	56
35	·6109	·5736	·7002	1·4281	·8192	·9599	55
36	·6283	·5878	·7265	1·3764	·8090	·9425	54
37	·6458	·6018	·7536	1·3270	·7986	·9250	53
38	·6632	·6157	·7813	1·2799	·7880	·9076	52
39	·6807	·6293	·8098	1·2349	·7771	·8901	51
40	·6981	·6428	·8391	1·1918	·7660	·8727	50
41	·7156	·6561	·8693	1·1504	·7547	·8552	49
42	·7330	·6691	·9004	1·1106	·7431	·8378	48
43	·7505	·6820	·9325	1·0724	·7314	·8203	47
44	·7679	·6947	·9657	1·0355	·7193	·8029	46
45	·7854	·7071	1·0000	1·0000	·7071	·7854	45
		Cosine.	Cotangent.	Tangent.	Sine.	Radians.	Angle.

ANSWERS

The following values have been used throughout, unless otherwise stated:

$g = 32$ ft./sec.^{2} or 981 cm./sec.^{2}.
Density of water $= 1$ gm./cm.^{3} or $62\frac{1}{2}$ lb./ft.^{3}.
Density of mercury $= 13 \cdot 6$ gm./cm.^{3}.
Atmospheric pressure $= 76$ cm. of mercury.

CHAPTER I. p. 21.

1. 60 ft. sec.$^{-1}$; 82·7 ft. sec.$^{-1}$; 3·78 sec. **2.** $32\frac{1}{4}$ m.p.h.
3. 95 ft. **4.** 32 ft. sec.$^{-1}$.
5. 480 miles per hr. per hr. ; 1440 miles per hr. per hr. ; 60 miles per hr.
6. 240 ft. **7.** 21·5 ft. sec.$^{-1}$; 35·5 ft. sec.$^{-1}$.
8. 57 ft. ; 9 ft. sec.$^{-2}$. **10.** 498·7 ft. **11.** 4·575 sec., 915 ft., 1250 ft.
12. $\frac{1}{2}gt^2$ ft. below balloon ; ut ft.
13. $u \cos \alpha$, $(u \sin \alpha - gt)$, $\dfrac{u^2 \sin^2\alpha}{2g}$, $\dfrac{u^2 \sin 2\alpha}{g}$, 45°.
16. 2400 ft. sec.$^{-1}$. **18.** 33·55 m.p.h., 26° 34′ E. of South.
19. 7 knots.

CHAPTER II. p. 44.

1. 5° 21′. **2.** 2·74 sec. ; 6 ft. and 10 ft.
3. $V \sin^2 \alpha \times 4 \cdot 82 \times 10^{-4}$. **5.** 605 poundals per sq. ft.
6. -6 and $+6$ ft. sec.$^{-1}$; 12 ft. poundals. **8.** $e = 2/3$.
9. $2m\sqrt{gl}/(M+m)$; $2 \sin^{-1} m/(m+M)$; $2glmM/(m+M)$.
11. 80 lb.-ft. sec.$^{-1}$; 320 ft. poundals ; 3·2 ft. sec.$^{-1}$.
12. $-8/3$ ft. sec.$^{-1}$; 5/6 ft. sec.$^{-1}$; 0·7. **13.** 667 ft. sec.$^{-1}$.

CHAPTER III. p. 81.

1. 375 lb. wt. **2.** $\sin^{-1} \dfrac{G}{aW}$, W.
3. If D is $\frac{1}{4}$AC from C, resultant acts at $\frac{1}{3}$DB from D.
4. $(4 \cos \theta - 2\sqrt{3} \sin \theta)$ lb. wt.
5. 2·5 lb. wt. bisecting angle BAC ; 9·68 lb. wt.

8. $\tan^{-1}\dfrac{(w_1-w_2)a}{2\mathrm{P}x+(w_1+w_2)x+\mathrm{W}(x+y)}$.

12. On the axis and $0{\cdot}403a$ from base.

15. (i) $\frac{2}{5}\mathrm{M}r^2$; (ii) $\frac{3}{10}\mathrm{M}a^2$.

16. $\frac{1}{8}\mathrm{M}a^2$; 3·704 inches.

17. 141·4 poundal-ft., 300 revolutions.

18. 3·142 sec.; 59·36 kg. wt. cm.

19. 2·83 ft. sec.$^{-1}$.

21. 18·5 lb. wt.

22. 119·7 ft. sec.$^{-1}$.

23. $\tan^{-1} 1{\cdot}443 = 55° 17'$ to the horizontal.

24. 80,000 poundals; 30 stone wt.

25. 980 cm. sec.$^{-2}$.

CHAPTER IV. p. 105.

2. 428·8.
3. 324·3 ft.; 6·37 ft.
4. 2·864 ft.; 12·99 ft. sec.$^{-1}$.
5. 0·7854 sec.; 42·67 ft.-poundals.
6. 8·46 ft.; 0·214; 28° 13′.
9. 51·5 ft.; 1·57 sec.
10. 980 cm. sec.$^{-2}$.
12. $2\pi\sqrt{3a/2g}$.
13. $3\sqrt{2}\,l$.
14. 0·04 cm. approx.; 6′.
15. $0{\cdot}229l$.
17. $2\pi\sqrt{2l(\sqrt{2}-1)/g}$.
18. $4\sqrt{2}a/3$.
19. $\mathrm{T}=2\pi\sqrt{(k^2+h^2)/gh}$, $m(a^2+b^2)/3$, $2\pi\sqrt{(4a^2+b^2)/3ag}$.

CHAPTER V. p. 124.

1. $6{\cdot}898\times10^{-8}$.
2. 988·3 cm. sec.$^{-2}$.
3. 3·779 sec.
4. 84·4 min.
8. 3·40 dynes.

CHAPTER VI. p. 150.

4. $7{\cdot}258\times10^6$ dynes.
5. 9·913 cm.
8. $mg+\sqrt{\dfrac{\mathrm{B}^2g}{mc}+m^2g^2}$ wt. units.
9. $fx^2/2l$, where f is the force to produce unit strain. 1·99 ft.
10. $m/\mathrm{M}=9/16$.
11. $\lambda x/l=w$.
12. 9/25.
13. 5×10^{-4} joule.
14. 0·429.
15. $1{\cdot}31\times10^{11}$ dyne cm.$^{-2}$.

CHAPTER VII. p. 179.

1. $\pi h^3\tan^2\alpha$ gm. wt. Thrust $=\frac{2}{3}\pi h^3\tan^2\alpha$ gm. wt. Pressure $=\frac{2}{3}h$ gm. wt./cm.^{2}.
2. $4a/3$ from top edge; $8a/9$ from bottom edge.
3. 0·0303 ft.
4. 500 lb. wt.
5. $2a/3$ in. from the b in. side, $\left(\dfrac{h}{2}+\dfrac{a\cos\theta}{3}\right)\Big/\left(\dfrac{h}{a}+\dfrac{\cos\theta}{2}\right)$ from the b in. side.
6. $5r/4$, 245 lb. wt., 49 lb. wt.
7. 255·5 gm., 44·5 gm.
8. Angle with horizontal $=\sin^{-1} h/l\sqrt{s}$.

9. 1·571 gm. wt.-cm.; 12·57 gm. wt. 10. 4·65 gm. wt.
12. 5 metres to level of water in tube. 13. 7·189 cu. m.
14. 69 ft. 15. 29·69 in. 16. 35 cm.
17. 53·34 metres. 18. 29·8 cm. 20. 77·16 cm.
21. Weight of tube and mercury column. Decreases owing to buoyancy of tube until tube is full. Then decreases to zero.
22. 14·6 inches of mercury.

CHAPTER VIII. p. 202.

1. $1/\sqrt{10}$ cwt. 2. 0·805. 3. 13 ft.
4. 1·706l. 6. (i) W tan $(\lambda+\alpha)$; (ii) W tan $(\lambda-\alpha)$; (iii) W sin $(\lambda-\alpha)$.
7. $a=\frac{1}{2}g(1-\sin\alpha-\mu\cos\alpha)$.
8. $a(\frac{1}{2}-\mu-\frac{1}{2}\tan\alpha)$ from the upper edge on the plane; $\frac{W}{2}(\cos\alpha-\sin\alpha)$.

CHAPTER IX. p. 214.

2. (a) 19·63 cm. (b) 7812 dynes. (c) No; provided that all the water reaches the wall. Because the horizontal velocity and momentum are unchanged by gravity.
3. 0·888 cm. of mercury. 4. 73·2 cm. of mercury.
6. 3001 c.c. per sec. 7. $9\cdot4\times10^5$ c.c. per min.

CHAPTER X. p. 228.

2. $1\cdot84\times10^5$ cm. sec.$^{-1}$. 4. $4\cdot93\times10^4$ cm. sec.$^{-1}$. 5. 1·469 gm. cm.$^{-3}$.
7. $2\cdot3\times10^{19}$.

CHAPTER XI. p. 248.

6. 0·691 standard atmos. 9. 57·8 cm. of mercury.
10. 10·1° C.

CHAPTER XII. p. 288.

4. 8·18 gm. wt. 5. 59·3 dyne cm.$^{-1}$. 7. 6·53 mm.
8. 1 : 6·52. 9. 0·0769 gm. wt.
10. (a) 1·51 cm.; (b) 1·75 cm. 11. 0·799 gm. cm.$^{-3}$.
12. 3·05 cm. The liquid will overflow until the tube is covered inside and out, and will then remain at rest.
13. 0·884 cm. 15. $1\cdot027\times10^6$ dyne cm.$^{-2}$.
16. 27·5 dyne cm.$^{-1}$.

CHAPTER XIII. p. 323.

8. $0\cdot01\sin2\pi(x/330-100t)$.

INDEX

PRINTED IN GREAT BRITAIN BY ROBERT MACLEHOSE AND CO. LTD.
THE UNIVERSITY PRESS, GLASGOW

Books on Physics

A Text-book of Physics for the use of Students of Science and Engineering. By J. Duncan; Wh.Ex., M.I.Mech.E. and S. G. Starling, B.Sc., A.R.C.Sc. 20s. Also in Parts: Dynamics, 7s.; Heat, Light and Sound, 8s. 6d.; Magnetism and Electricity, 7s.

Intermediate Practical Physics. By T. M. Yarwood, B.Sc. 7s. 6d.

A Text-book of Practical Physics. By H. S. Allen, M.A., D.Sc., and H. Moore, A.R.C.Sc., B.Sc. Second Edition. 12s.

Mechanical Properties of Matter. By S. G. Starling, B.Sc. 8s.

A Text-book of Light. By G. R. Noakes, M.A. 7s.

A Text-book of Heat. By Prof. H. S. Allen, M.A., D.Sc., F.R.S. and R. S. Maxwell, M.A., B.Sc. Part I (Intermediate Degree Standard). 12s. Part II (Degree Standard). 10s. 6d.

A Text-book of Electricity and Magnetism. By G. R. Noakes, M.A. 8s. 6d.

Magnetism and Electricity for Students. H. E. Hadley, B.Sc. 8s. 6d.

MACMILLAN AND CO. LTD., LONDON